DOE

ENERGY STORAGE

SYSTEMS PROGRAM

Quarterly Progress Report

for

June — September 2003

(Fourth Quarter / Fiscal Year 2003)

Energy Storage Systems Department (ESS)

Sandia National Laboratories
Albuquerque, NM

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System Integration

Alternative RGS System Designs to Improve Battery Performance

SNL Contact: Stan Atcitty
Contractor: Electrochemical Engineering Consultants, Inc. (EECI) – Dr. Philip C. Symons
FY03 Funding: $130K

Project Overview

The purpose of this alternative configurations project is to develop and validate integrated devices that will improve system reliability and component performance, plus reduce the life-cycle-costs of continuous power systems such as renewable generation systems (RGS). Currently, the primary objective of this project is to provide a means to optimally manage the charging and discharging of the energy storage batteries in RGS solar-hybrid systems.

Secondary objectives for the work include improving the communications among battery suppliers, power converter developers, and customers; and evaluating the utility of the methods developed in the work to other battery applications, such as provision for standby power.

Work began on this project during the fourth quarter of FY98, when several alternative configurations were conceptualized and modeled to verify that the design concepts would lead to improved system performance for batteries in hybrid power systems and that might ultimately reduce life-cycle-costs.

Following the construction and testing of some laboratory and breadboard systems in early FY99, prototypes of one of the alternative configurations (called ACONF) were built and tested to validate the modeling work during the latter part of FY99 and through FY00. The first prototypes developed were designated as 10kW class units.

In FY01 and FY02, three copies of the most-advanced prototype were built. Two of these prototypes are currently being tested at the Arizona Public Service Solar Test and Research (STAR) Facility in Tempe, AZ. The STAR Facility is owned and operated by Arizona Public Service, which has several semi-commercial PV hybrid sites. (See: *PV/Hybrid Controller Field Test*, this report). The third was installed at the Sandia National Laboratories (SNL) Photovoltaics System Evaluation Laboratory (PSEL) and is undergoing testing there with a 24V AGM VRLA battery. (See: *Advanced Battery Management System*, this report).

Fourth Quarter Status

The ACONF units at the STAR Facility have operated reliably for more than two years, even during the extremely hot summers at that location. Data is collected from them weekly before being sent to EECI for analysis. During this quarter, analyses indicated that there might be a poor contact at one point of one of the printed circuit boards of the system. Operation of the RGS solar hybrid systems with which the ACONF units are being used were not impacted by this poor contact, because measures have been built into the units to prevent any problems arising from any ACONF malfunction. The poor contact issue is currently being actively addressed so that modifications can be made to the failing part to prevent any recurrence of this in future units.

The ACONF unit at PSEL with VRLA batteries has continued to operate without major problems for more than nine months. PSEL testing confirms that the ACONF technology can be used to charge VRLA batteries to a level that should ensure that the capacity of the cells will be maintained at the highest possible level.

Further improvements continue to be made to the ACONF units by making minor adjustments to hardware and software to improve operability. The bypass switches that were installed earlier in FY03 proved their worth when the poor contact problem discussed above came to light. The bypass switches help ensure continuous operation of the PV hybrid systems even during a failure, however rare, of the ACONF system.

Testing of the voltage-temperature sensors that were installed earlier in the year on the ACONF units at STAR and at the SNL Distributed Energy Technology Laboratory (DETL) continued. The sensors seem to be operating correctly; but data collection on the units has been suspended pending use of these sensors to limit charge and discharge with ACONF software modifications that are currently underway. The voltage-temperature sensors are needed for the high-power ACONF units that have been under development this year.

In fact, development to the high-power ACONF unit has been the main focus of activity on the ACONF project during the last six months of FY03. Much of the time was spent in developmental testing of the first of these high power units (designated Unit 1B) at a sub-contractor, before it was decided to take a radically different design approach with the next few units. Unit 2B, with the new design, was installed at the DETL late in this quarter. See Figure 1.

Figure 1. ACONF Unit #2B at DETL.

The high power (100kW class) units that have been developed have a capability of 33kW for each string, and incorporate a novel, relatively low-cost, approach for providing power for finish charging. Unit 2B at DETL is set up for operation with a two-string, VRLA gel battery (manufactured by Yuasa in 1996) and is rated at 33kW. The battery is connected to a Xantrex (Trace) converter rated at 30kW (480V 3-phase AC) that is connected to the grid in lieu of a generator, and for which there are a variety of load banks that can be connected for testing as necessary. A solar PV array can also be connected in when required.

Testing of the high-power Unit 2B has only recently begun at the DETL; so there is little data available to report on as yet. The unit appears to operate satisfactorily and reliably; but refinement of the finish charge hardware is required before the unit can be put into automated testing. Tests to complete the design of the controls for the refined finish charge hardware are currently underway.

A third, high power unit (Unit 3B) has already been fabricated and factory-tested, and after modification to incorporate the refined finish charge hardware, Unit 3B will be installed and tested in the APS STAR Facility Hybrid Test Building.

Hardware Prototype of Device to Improve Transient Loadability of Distributed Energy Resources

SNL Contact: Stan Atcitty
Contractor: New Mexico State University, Las Cruces, NM — Dr. Satish J. Ranade
FY03 Funding: $21K

Project Overview

The purpose of this project is to develop a prototype for an energy storage-based device to improve transient load performance of Distributed Energy Resources (DER). Such a device can help allow stable islanded operation of an isolated DER grid. The project has resulted in a three-phase prototype device that will permit comprehensive evaluation of potential benefits, as well as insight into using electrochemical capacitors as energy storage elements.

DER often cannot operate when isolated from a utility because the inverter at the interface is unable to handle large transient loads, such as motor starts. This device uses an electrochemical capacitor to supply energy for short periods for transient loads. As shown in Figure 1, an electro-chemical capacitor, or other storage source, is interfaced to the DER terminals using a simple, short-term rated, dc-ac inverter. At the onset of a large transient load, the capacitor supplies the excess current needed. As a result, the DER can ride the disturbance out. The feasibility of the concept depends on the cost and performance of energy storage elements and optimized design of the inverter.

A single-phase prototype was fabricated and demonstrated in the first year of the project, FY02, and a disclosure of technical advance was filed at SNL.

During the first two quarters of FY03, work focused on developing a three-phase prototype. An optimum design for the device was completed during the third quarter. Additionally, efforts have included examination and documentation of the performance of several commercial capacitor technologies as energy storage elements. During the third quarter, two prototypes were fabricated and tested with several capacitor technologies.

Fourth Quarter Status:

Fourth quarter activities focused on extensive tests of the three-phase prototype using three different electrochemical capacitor technologies; namely: ESMA capacitors, Evans hybrid capacitors, and Maxwell capacitors. Figure 2 illustrates DER current, motor current and device current during a motor start. The tests suggest that all capacitors can perform satisfactorily. However, the two latter technologies appear to be better suited because of they are available in sizes that better match requirements. Comparative results will be presented at the 2003 EESAT Conference.

A three-phase prototype that allows direct measurement of device temperature has also been completed. This will allow detailed thermal analysis with a view to optimizing inverter design.

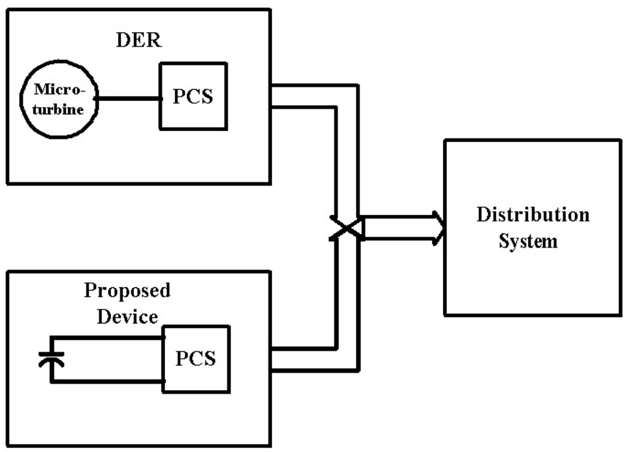


Figure 1: Proposed Device To Improve the Transient Loadability of a DER

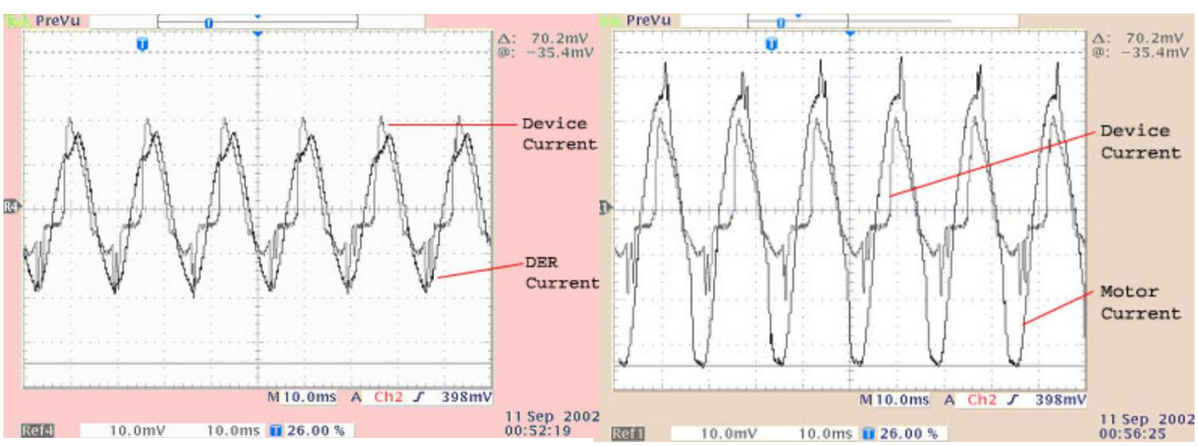


Figure 2. Device operation with ESMA Electrochemical capacitor. DER current and Device current (left), Motor starting current and Device current (right).

Integration and Testing of Energy Storage with Flexible AC Transmission System (FACTS) Devices

SNL Contact: Stan Atcitty
Contractor: University of Missouri-Rolla – Dr. Mariesa L. Crow
FY03 Funding: $57K

Project Overview

The purpose of this work is to investigate the integration of BESS into bulk power systems through an interface with FACTS devices. This project was initiated in April 1998 to investigate the feasibility of interfacing battery energy storage into an existing laboratory scale FACTS device.

Over the next two years, several prototype FACTS/BESS devices were designed, built, and tested. 2001 and 2002 focused on designing power electronics topologies to best exploit the active power capabilities of BESS. Several multi-level converters were identified, designed and built. Additional theoretical analyses developed comparison metrics to determine the impact of the various FACTS/BESS devices on bulk power system stability.

This work provided clear experimental and theoretical support that adding energy storage capabilities to existing FACTS devices provides superior performance and control.

There are several compelling reasons to consider a multilevel converter topology for the StatCom/BESS. Well-known reasons include lower harmonic injection into the power system, decreased stress on the electronic components due to decreased voltages, and lower switching losses. Various multilevel converters also readily lend themselves to a variety of Pulse Width Modulation (PWM) strategies to improve efficiency and control. The use of multilevel converters can readily reduce the size of the individual energy storage units without compromising performance.

One additional advantage of incorporating energy storage and the StatCom is that the converter DC link capacitor can be significantly decreased, because only a small capacitor is required to smooth the DC current seen by the battery.

In 2003, two multilevel converters, the cascaded and the diode-clamped converters, have been compared and contrasted to ascertain the advantages and disadvantages of each topology for the StatCom/BESS.

Fourth Quarter Status

Work in the fourth quarter of 2003 concentrated on comparing battery configurations for the diode-clamped StatCom/BESS and experimental verification of the cascaded StatCom/BESS.

To provide as even a comparison as possible between topologies, the three StatCom/BESS controllers (cascaded, diode-clamped, and traditional) have been designed to have the same number of batteries and PWM base switching frequencies. The cascaded StatCom/BESS utilizes 36 batteries in six strings of six batteries each at 72V dc voltage. The diode-clamped StatCom/BESS shown in Figure 1 utilizes 36 batteries in four strings of eight batteries, each at 108V dc voltage. The operating features of these topologies were summarized in the FY03 third quarter report.

One attractive feature of the diode-clamped topology is that several connections can be used to better utilize the StatCom/BESS. For example, the number of batteries can be reduced by placing them across only half of the DC link capacitors (C_1 through C_4). As shown in Figure 1, strings of batteries can be placed in parallel with each DC capacitor to comprise four battery sets. In this project, a total of 36 batteries were considered, with one string of nine batteries across each capacitor. With the aid of an external balancing circuit, the battery sets across capacitors C_1 and C_4 can be eliminated, leaving only two sets of batteries.

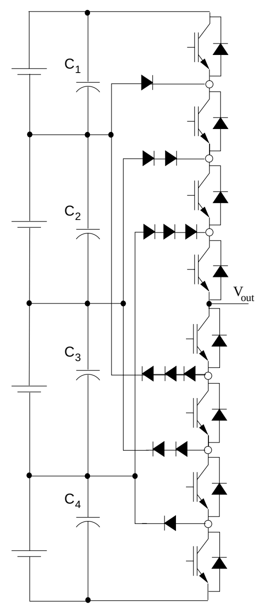


Figure 1: Diode-clamped StatCom/BESS (one phase

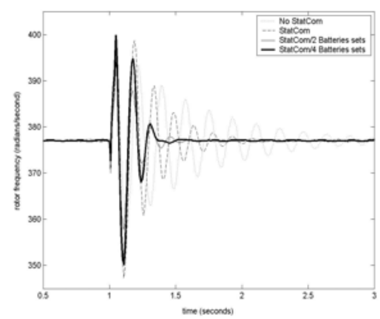
The external balancing circuit will automatically balance the active and reactive power output of the DC sources, thereby providing comparable performance to a traditional StatCom/BESS under moderate operating conditions. This ability is illustrated in the examples below, in which a system is subjected to a three-phase fault of various durations. The response of the diode-clamped system for no StatCom, StatCom, StatCom/BESS with 2 battery sets (18 batteries), and StatCom/BESS with 4 battery sets (36 batteries) are compared.

The waveforms shown in Figure 2 (a)-(c) are the rotor speeds of the generator in the test power system. If a fault is applied to the system, the rotor frequency will return to 377 radians/second (60 Hz) if the system is stable, otherwise the generator will experience “run-away” which leads to loss of synchronism.

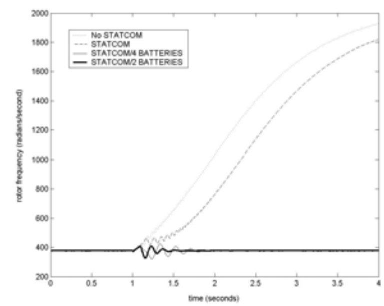
Figure 2 (a) shows the response of the system to a three-phase solid fault. Four different scenarios are depicted: i) no StatCom, ii) a diode-clamped StatCom with no BESS, iii) a diode-clamped StatCom with two battery sets, and iv) a diode-clamped StatCom with four battery sets. The system is stable under all scenarios, since the rotor frequency returns to 377 radians/second. With no StatCom, however, the system experiences undesirable poorly-damped oscillations.

In Figure 2 (b), the same set of scenarios (i)-(iv) is shown for a fault duration of 0.095 seconds. In this case, both the system and the system with a StatCom become unstable, but the StatCom/BESS is able to maintain stability.

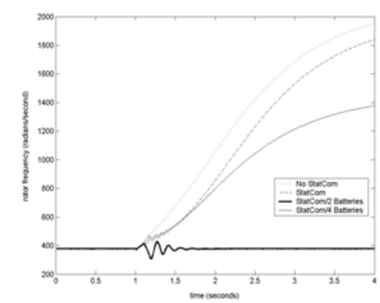
In Figure 2 (c), the fault duration is 0.11 seconds, and all but the system with the StatCom with 4 batteries go unstable. This result indicates that the diode-clamped StatCom/BESS can indeed provide system stabilization. It also indicates that more active power capability provides superior control, although moderate active power capability is still better than no active power capability.



(a) Rotor frequencies for a fault lasting 0.05 seconds



(b) Rotor frequencies for a fault lasting 0.095 seconds



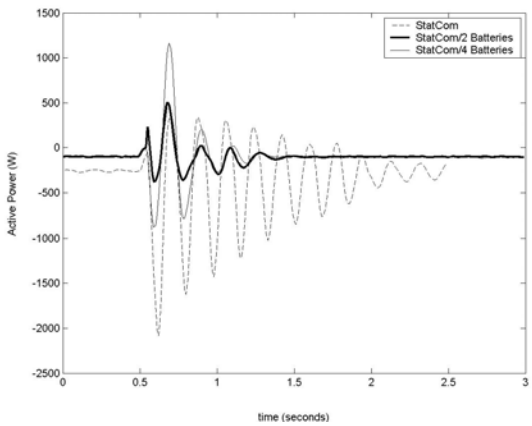
(c) Rotor frequencies for a fault lasting 0.11 seconds

Figure 2: Comparison of rotor frequencies for a system containing no StatCom, a StatCom, a StatCom/BESS with two Battery sets, StatCom/BESS with four Battery sets

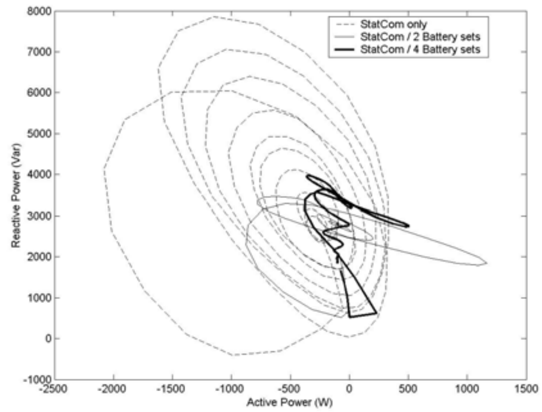
A comparison of the injected active power for the 0.05 second fault is shown in Figure 3. The difference between the two and four battery set StatCom/BESS can be clearly observed. Although the two battery set StatCom/BESS injects more active power than the four battery set into the system, it also absorbs considerably more active power from the system.

The StatCom also absorbs a large amount of active power from the system. This is due to the need for active power to compensate for the losses in the transformer and power electronics; whereas the StatCom/BESS with four batteries draws the active power from the battery.

Thus, there is a greater "net" amount of active power injection immediately following the fault to damp the system oscillations. This comparison supports the assertion that a multi-level diode-clamped StatCom/BESS with only two battery sets can achieve nearly the same transient stability support as the same topology StatCom./BESS with four battery sets, leading to significant cost savings.



(a) P_{inj} vs t for a 0.05s fault



(b) P_{inj} vs Q_{inj} for a 0.05s fault

Figure 3: Comparison of injected powers for a 0.05 s duration fault

Work during this quarter also focused on experimentally verifying the four-quadrant control capabilities of the cascaded StatCom/BESS. Experimental results showed that the multi-level cascaded StatCom/BESS is able to effectively operate in all four quadrants, as it was designed. The results indicate that the active and reactive power control can be independently controlled to achieve any reference setting desired (within the physical limitations of the StatCom/BESS).

NMSU Capstone[1] Design Project: Apparatus For Testing Charge/Discharge Characterisitics Of Supercapacitors

SNL Contact: Stan Atcitty
Contractor: New Mexico State University (NMSU) — Dr. Satish J. Ranade
FY03 Funding: $5K

Project Overview

The purpose of this education-related project is to introduce engineering students to electric energy storage and related technology through a Design Project class at New Mexico State University in the Klipsch School of Electrical and Computer Engineering. Requirements for all design projects in the class are developed in areas of interest to the DOE/ESS program.

Klipsch requires that all BSEE students complete a six-credit design class. Students with senior standing must design a reasonably complex system, drawing upon several specialties, such as power, electronics, computers, control, etc. The class provides significant experience in interdisciplinary teamwork, written and oral communication,

1 Here “Capstone” refers to the final class taken by students and not to a commercial brand of microturbine!

and leadership. The Accreditation Board for Engineering and Technology calls such classes “Capstones,” since this is the final class that students take.

DOE has an interest in the use of electrochemical and double-layered capacitors (so-called ‘Super-capacitors’ or ‘Ultra-capacitors’) as energy storage media in power system applications. That area of energy management was instituted in the first design project, offered in FY02, in which students successfully designed and fabricated a “Super-capacitor Test System.” SNL served as the ‘customer’ and students made mid-term and final oral presentations to SNL personnel.

For FY03, the design class project consisted of the following system requirements:

- Power electronics suitable for charging and discharging super-capacitors according to a specified protocol;
- A user interface based on National Instruments hardware and Labview software; the interface to allow a user to select and run test protocols, collect and display voltage, current, power and energy waveforms, and calculate and display performance metrics; and
- Software necessary to implement specific protocols such as constant power discharge.

Deliverables consist of the test system hardware and software, user manuals, and a demonstration.

While the FY02 project focused on a prototype system, the FY03 project is directed towards producing a usable product. Therefore, students must carefully consider protection and safety requirements, as well as packaging.

The proposed class was approved in the second quarter. At students request, the class was formally scheduled for Fall 2003; i.e., the fourth quarter of FY03.

Fourth Quarter Status

A team of four students commenced work on their six-credit Capstone class design project in August 2003. Based on required specifications, the team has outlined the hardware and software requirements for the project, and has developed work assignments, a management approach, and a set of milestones.

The team made their first formal technical presentation to Mr. John Boyes and Mr. Stan Atcitty of Sandia National Laboratory, who serve in the role of “Customers” on behalf of the DOE.

The team has begun developing software and the design and fabrication of the hardware. Periodic presentations will be made to NMSU faculty; and progress reports will be posted at http://www.ece.nmsu.edu/~ranadec.

The team expects to accomplish project goals by December 10, 2003, at which time a formal presentation will be made to Sandia National Laboratories personnel.

This project provides significant visibility for the energy storage area and DOE programs among the undergraduate and graduate student body at NMSU. It introduces students to important areas of energy management and trains them in the technologies that they will use in their careers. Therefore, the Capstone project at NMSU is important to DOE's mission to develop and disseminate technology.

<u>RAPS Testing Methods</u>

SNL Contact: Paul Butler
Contractor: Energetics, Inc. — Ed Skolnik
FY03 Funding: $57K

Project Overview

The DOE ESS Program at Sandia continues to coordinate with the International Lead Zinc Research Organization (ILZRO) on a project to define standard test-cycle regimes for remote area power supply (RAPS) systems. In FY99, a major decision was made to integrate this project with the existing infrastructure of the Institute of Electrical and Electronics Engineers (IEEE) Standards Coordinating Committee (SCC) 21, Fuel Cells, Photovoltaics, Dispersed Generation, and Energy Storage. The documents in process in the Energy Storage Subsystems Working Group (ESSWG) of SCC 21 all relate to distributed energy resource energy systems with battery storage used in a stand-alone mode (no utility connection).

Sandia, ILZRO, and Energetics Inc., a contractor to SNL on this project, are coordinating the activities of the ESSWG and are preparing new guidelines for RAPS systems — those that use a renewable generation resource, energy storage, and a fossil-fueled generator in a stand-alone mode. Work is in progress on three Project Action Requests (PARs) and on the review of two existing standards:

<u>PAR 1361</u> – Guide for Selection, Charging, Test and Evaluation of Lead-Acid Batteries Used in Stand-Alone Photovoltaic Systems (Status: Approved)

<u>PAR 1561</u> – Draft Guide for Sizing Stand-Alone Energy Systems (Draft 7)

PAR 1562 – Draft Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems (Draft 1)

Standard 1013-2000 – Draft Recommended Practice for Sizing Lead-Acid Batteries for Photovoltaic (PV) Systems

Standard 937-2000 – Recommended Practice for Installation and Maintenance of Lead – Acid Batteries for Photovoltaic (PV) Systems

At an ESSWG meeting in June 2003, the group agreed to modify the scope and purpose of PAR 1561 and change the title to "Guide for Optimizing the Performance and Life of Lead-Acid Batteries in Hybrid Remote Area Power Supply Systems." The attendees reconciled some of the language in PAR 1561 and other related documents, focusing primarily on clarifying definitions and terminology.

Fourth Quarter Status

The ESSWG had no meetings in the fourth quarter of FY03. A meeting is scheduled for early in 2004.

Peru System Monitoring

SNL Contact: Paul Butler
Contractor: International Lead Zinc Research Organization (ILZRO) — Jerry Cole
FY03 Funding: $22K

Project Overview

In July 1997, the International Lead-Zinc Research Organization (ILZRO), the U.S. Solar Energy Industries Association (SEIA), and the Ministry of Energy and Mines of the government of Peru signed a Memorandum Of Understanding (MOU) for a collaborative project to design, install, and operate advanced, remote area power supply (RAPS) systems that include lead-acid batteries in isolated, off-grid locations.

The goal of this pilot project is to demonstrate that battery-based hybrid power systems are technically and financially viable options for rural, off-grid electrification. This goal applies to not only the technical aspects of the equipment, but also to the social and economic development needs of the rural, remote communities.

The first phase of the project was a feasibility study for photovoltaics in combination with storage, power electronics, and controls for use in remote villages along the Amazon River valley, and included an estimation of the economic benefits. The MOU signatories and the ESS Program shared the cost of the study. An ILZRO report documents the results.

With funding provided by DOE/ESS and ILZRO (through the Peruvian government, the World Bank and other financial institutions), the project entered the hardware development and installation phase near the end of FY01 and continued throughout FY02. Orion Energy of Frederick, MD, is the system integrator for all the equipment and is developing the data acquisition system (DAS) with DOE/ESS support. Two villages are to serve as prototype test sites: one with a 30-kWp electric system and another with a 60-kWp system.

During the third quarter, the 30-kWp system was installed at Padre Cocha in the Loreto Province of Peru. Soon after energizing the system, voltage regulation problems with the generator and issues with several printed circuit boards in the RAPS system power electronics were identified, resulting in less-than-rated output from one of the battery charging circuits. A partial repair was implemented. In addition, the system was operated in an overload mode. This occurred in spite of the energy efficiency training provided to the local population by the RAPS team. Changes were made in the village loads to reduce the energy consumption to lower levels, in order for the RAPS system to be operated at its design rating.

Padre Cocha PV Array

Fourth Quarter Status

In the fourth quarter, the supervisory software was modified to integrate the data acquisition system with the monitoring controller, so data would become available as soon as the Padre Cocha system went online.

Once the system installation was complete, it was energized and a debugging process initiated. At the start of operations, several problems were encountered.

- Voltage regulation problems with the generator (not part of the RAPS installation).

- Malfunction of several printed circuit boards in the RAPS system's power electronics, which resulted in less-than-rated output from one of the battery charging circuits.

- Modestly out of date distribution issues having to do with the village T&D infrastructure.

- Data transfer issues caused by failed cards in the charge controller, which prevented the monitoring computer from downloading data.

All of these and other problems have been addressed and the system was operational as of October 2003.

The 60-kWp RAPS system for the other village (Indiana) is scheduled to be installed once Padre Cocha demonstrates nominal operations.

ABESS (Advanced Battery Energy Storage System) / PV System

SNL Contact: Nancy Clark
Contractor: ZBB, Inc. — Robert Parry
FY03: FY02 Carryover Funds

Project Overview

The ESS Program (ESS) has a long-term commitment to develop zinc bromine batteries with ZBB. This project provides field-testing for two ABESS (advanced battery energy storage systems), rated at 200kW/400kWh and 50kW/100kWh and based on zinc bromine battery technology, in load-leveling/peak shaving applications.

Under the contract, ZBB built a 400kWh/200kW system in cost-shared contracts with ESS. The first real-time test of the system was in 2000 at the Detroit Edison Akron site, which has power quality problems during the fall grain-drying process. The test proved successful and four batteries from the unit were returned to ZBB for re-furbishing.

In August 2001, the system was moved to the Detroit Edison Lum site, which requires load leveling in the summer. After solving many interconnection issues, the system ran successfully into the fall season of 2001. Detroit Edison and ZBB then decommissioned the system and returned all the batteries to ZBB's factory for re-conditioning and further testing.

ESS has begun a second project with ZBB that calls for a 50kW/100kWh system. Called the "Greenpoint PV-Battery System," PowerLight has contracted with the Greenpoint Manufacturing and Design Center (GMDC), a non-profit arts and industry organization that purchases and rehabilitates historic buildings in the Greenpoint area of Brooklyn, to install a 50 kWac PV system at PowerLight's Humboldt Street facility (GMDC holds the Con Edison accounts for this facility and uses sub-meters to bill each tenant separately). The coincident daily peak load of the building on business days is roughly 80 kWac.

PowerLight decided to use the Humboldt facility as the site to integrate one of ZBB's three zinc-bromine 50kW/100kWh battery systems (Trade Name: NYSERDA Hi-Value) with a 50 kWac PV system to absorb weekend PV production and dispatch it throughout the week to help reduce the customer load. The PV-Battery system can, therefore, be described as having a 75 or 80 kW peak.

After refurbishing the stacks, and before installing the Greenpooint system at the Humboldt site, ZBB began running them through a series of qualifying tests that measure fault and shutdown conditions, charge/discharge rates at specific AC power levels, and automatic startup performance following a power outage.

During the third quarter of FY03, the 100-kWh system responded appropriately, within expected parameters, to error-handling tests that verified system operation and recovery during unusual conditions, including erroneous commands. It also successfully performed a 48-hour prequalification test, controlled by the system's hybrid system controller (HSC), with the system at 100% SOC. This led to an examination of the system's SOC function. Because the system's SOC function does not take into account self-discharging, small inaccuracies can become quite significant after a number of consecutive cycles; therefore, a decision was made to modify the SOC accordingly.

ESS and ZBB expected the NYSERDA Hi-Value battery system to be delivered to the Humboldt site during the FY03 fourth quarter.

Fourth Quarter Status

The NYSERDA Hi-Value battery system was delivered to the Humboldt site on schedule and is awaiting startup.

Li Ion BESS

SNL Contact: Nancy Clark
Contractor: SAFT, Inc. — Salah Oweiss
FY03 Funding: FY03 Cost-Sharing Funding

Project Overview

The immediate goal of this project is to design and construct a 100 kW/1 minute (1.67 kWh) Li-ion battery energy storage system for use in providing power quality for grid-connected microturbines.

This project is part of the ESS Program's advanced energy storage (AES) component development initiative. The purpose of the initiative is to support the improvement of AES components (such as flywheels, superconducting magnetic energy storage (SMES), and electrochemical capacitors). The ultimate goal of the initiative is to develop and test AES components large enough to be used in field demonstrations and to find industry partners to support these field demonstrations (including cost sharing).

Portable lithium-ion (Li-ion) batteries are widely available for a variety of commercial applications (cell phones, laptop computers, etc.). However, larger cells and batteries based on Li-ion technology are still in the early stages of development. Consequently, although commercially available battery technologies were not included in the scope of the AES initiative, SAFT's proposal for an energy storage system based on Li-ion batteries was accepted because it represented the significant further development of an advanced battery technology that was not commercially available for non-portable applications.

The main advantages of a Li-ion system over conventional batteries is its high-energy density and good cycle life (for both deep-discharge cycling and shallow cycling). Additionally, compared to conventional battery systems, Li-ion systems are relatively low maintenance. Although they do require monitoring to prevent overcharging, to a large extent this monitoring can be accomplished with computer technology, as opposed to maintenance which requires relatively expensive human labor.

The work completed during this project should help to realize the advantages of Li-ion technology for applications where more traditional battery types (specifically lead-acid) are now used. Further, it is hoped that with wider use in larger applications, this technology can eventually compete with lead-acid batteries on a cost-per-life-cycle basis.

To date, two complete systems have been designed and assembled. Factory acceptance testing was successfully completed on both systems and they were sent to the appropriate utility partners, Southern Company Services (SCS) and American Electric Power (AEP), for field qualification.

Fourth Quarter Status

The field demonstration at SCS uses the BESS (battery energy storage system) to supplement distributed generation (via microturbine) and to provide load following capability. The system was installed at the demonstration site and commissioning tests were successfully completed.

The system was run at its rated power level of 100-kW for three minutes, which exceeded the battery design requirements by a factor of three. Figure 1 illustrates the preliminary test results.

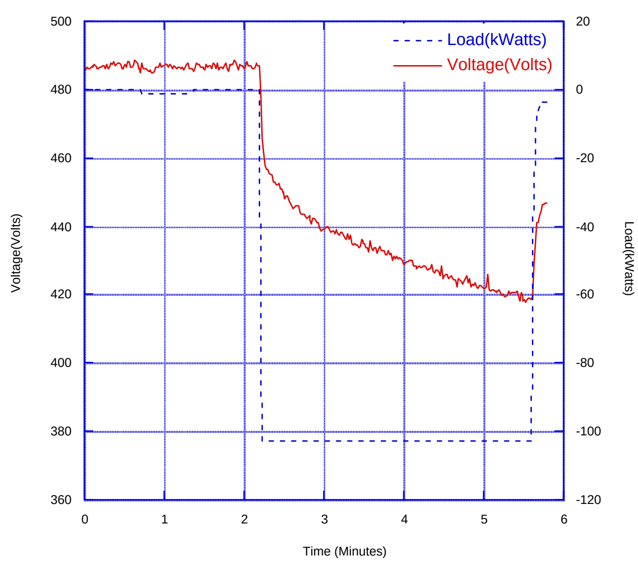


Figure 1. Preliminary test results of the 100-kW BESS at Southern Company.

The second system was delivered to American Electric Power (AEP) and commissioning tests were performed successfully. The system was configured as a standalone UPS and was available for 1146 hours during field testing. Test results are shown in Figure 2.

The final version of the system's operations manual was completed and distributed to all of the partners.

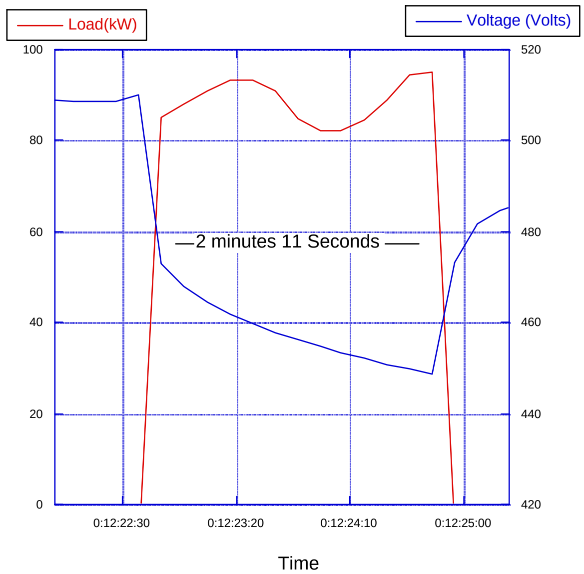


Figure 2. Preliminary test results of the 100-kW BESS at AEP.

PV/Hybrid Controller Field Test

SNL Contact: Garth Corey
Contractor: Arizona State University (ASU) — Bob Hammond
FY03 Funding: $51K

Project Overview

The ESS Program owns a large CR9000 Data Acquisition System (DAS), located at the APS STAR facility (Arizona Public Service Solar Test and Research Center) Hybrid Test Facility in Tempe, AZ. This DAS is currently on loan to APS to assist them in evaluating off-grid hybrid systems being tested at the APS STAR Hybrid Test Facility. In return, APS has agreed to share test results to increase our data base on off-grid hybrids. ASU is responsible for the operation and maintenance of the DAS and is responsible for all data management activities and limited analytical support for data collected at the Hybrid Test Facility.

ASU STAR and SNL have been collecting data and monitoring activity on the Alternative Configuration project under test at STAR. ASU is tasked with all data management activities associated with this activity.

Sandia continues to consult with the APS STAR team on activity at Carol Springs Mountain (CSM), following the re-powering of the energy storage system with Absolyte IIP batteries. The site is located on a remote mountaintop approximately 106 miles from the STAR Center in Tempe.

The Carol Springs system consists of a 26 kW PV array, a 53 kW diesel generator, a 30 kW AES bi-directional inverter, and a 600 kWh Absolyte IIP VRLA battery configured in three parallel, 200 kWh strings. The average load at the remote telecommunications site is approximately 17 kW. Sandia has a DAS installed at the CSM site that provides operational data to both APS and Sandia.

Because of SNL's interest in analyzing the performance of an Absolyte IIP battery from its commissioning until its shut-down, APS has provided a unique opportunity to complete a lifetime analysis on a large battery. As a result, SNL has entered into an agreement with APS to provide monitoring and data management for the new battery and has developed a plan for the ASU Team to perform these activities under the current APS contract.

To create a baseline record for the integrity of the battery at Carol Springs Mountain, an initial ohmic measurements were taken shortly after the new battery was installed almost two years prior. Since then, three sets of ohmic measurements have been taken at six month intervals and were analyzed during the third quarter of FY03.

The battery is stable and continues to perform without incident. Data acquisition and archival for tracking battery performance also continues. Analysis of the data and trend studies are scheduled for FY04.

Fourth Quarter Status

There was no activity at Carol Springs Mountain during this quarter. Ohmic measurements are scheduled for the first quarter, FY04.

Alternative Configuration testing continues at STAR and the test program continues to collect, analyze, and archive data from the two off-grid systems undergoing testing.

<u>Data Analysis from PV/Hybrid Controller Testing</u>

SNL Contact: Garth Corey
Contractor: Electrochemical Engineering Consultants, Inc. (EECI) — Phil Symons
FY03 Funding: $25K

Project Overview

For the past two years, data has been collected and archived by Arizona State University (ASU) at the Arizona Public Service (APS) Solar Test and Research (STAR) Center Hybrid System Test Facility, using a Data Acquisition System (DAS) supplied and maintained by SNL (See: ***PV/Hybrid Controller Field Test***, above). EECI is the primary analyst and consultant for the project and is responsible for generating quarterly reports that evaluate the effectiveness of the operational strategies employed at the Hybrid System Test Facility.

Tracking the life history of a Yuasa tubular gel, 210 kWh battery on loan from APS and installed at the Sandia DETL is a primary task for EECI. The Yuasa battery is being routinely cycled at the DETL using the Trace 30kW inverter. This inverter is the primary inverter for the test program that includes testing for both the Yuasa tubular gel battery and a high power (100 kW) Alternative Configuration (ACONF) controller to be installed on the battery.

Final manufacturing preparations for the ACONF were completed during the third quarter of FY03, with delivery and installation of the unit expected during the fourth quarter. This is the first 240 VDC system managed by an ACONF system.

Fourth Quarter Status

The first high power, 100 kW, ACONF unit complete with voltage/temperature sensors was installed on the Yuasa battery system during this quarter. Initial test results indicate that the unit is operating properly.

Because of the high cost of an upverter for the unit at the higher voltage and currents, an innovative approach was taken that uses a battery substring of sufficient voltage to provide the finishing current for the battery. The innovation is operating well at substantially less cost than the upverter. The plans are to engineer an upverter for commercial systems once the high power unit has been proven.

Natural Gas-Fueled, 5kW, Continuous Power Fuel Cell

SNL Contact: Garth Corey
Contractor: Plug Power — David Rollins
FY03 Funding: $25K

Project Overview

Fuel cells are referenced as an energy storage component in the Energy Storage Systems Program (ESS). Therefore, it is important to understand how fuel cells operate in the DER environment.

Late in FY02, under a "cradle-to-grave" procurement contract with Plug Power, ESS acquired a 5 kW Plug Power SU1 CHP (combined heat and power) fuel cell for testing at the Distributed Energy Test Laboratory (DETL) at SNL. The fuel cell, which has the capability to operate grid-tied or stand-alone, will be operated and tested in both configurations.

The purpose of this program is to characterize the fuel cell for operations above 5000 ft altitude and provide performance data for both on-and-off-grid operations. The fuel cell will also become a power generation component in the DER test program and will be connected to the DETL Micro Grid after characterization is complete.

Under provisions in the contract, two Sandia personnel who were trained in the system, installed the Plug Power SU1 CHP fuel cell at the DETL early in the second quarter of FY03and continue to operate and maintain it with technical support provided by Plug Power.

The unit went on-line at an output of 2.5 kW, with power being dispatched to the grid, and shakedown testing was completed early in the third quarter. Further testing was completed that replicated the factory acceptance tests. These tests provided characterization data for the operation of the unit at high altitude.

During the third year of the contract, the fuel cell unit will be upgraded to the most recent advancement in hardware and software to maintain the system at the current state of the art.

Problems with low power output were experienced late in the third quarter, caused by an operational algorithm that did not fully account for operation at the DETL's high altitude. Coordinating with Plug Power, Sandia engineers analyzed the problem and implemented changes that brought the unit back to full power. Planning was initiated to test the unit in an off-grid application to determine the transient response of the fuel cell.

Standalone testing is scheduled to commence early in the fourth quarter.

Fourth Quarter Status

The system operated sporadically at low power throughout the quarter. Late in the quarter, the fuel cell stack was replaced and the system was brought back on-line. However, change-out of the stack did not solve all of the power problems and interaction with PlugPower continued through the end of the quarter, in an effort to restore the unit to full operation.

Vernon & Metlakatla VRLA Battery Monitoring

SNL Contact: Rudy Jungst
Contractor: Exide Technologies, GNB Network Power Division — George Hunt, Rob Schmitt
FY03 Funding: FY02 Carryover Funds

Project Overview

VRLA (valve-regulated lead-acid) battery systems have been in place at the GNB Battery Recycling Facility in Vernon, California, and at the village Metlakatla, Alaska, for several years. The BESS at the Vernon smelter, a battery-recycling center, was first installed in 1995 (Figure 1). It consists of two strings of 378 modules each of 4800-Ah

Absolyte batteries (9600-Ah on site). The BESS for Metlakala Power and Light (MP&L) was installed in 1996 and consists of one string of 378 modules of 3600-Ah Absolytes.

The different use profiles in the two locations provide a unique opportunity to compare two very similar types of VRLA cells in different use environments. Vernon continued to peak-shave at 3150 kW on weekdays during peak demand times (currently 16:00 to 22:00 PST); and Metlakatla is always on-line, reducing fuel consumption on the island to virtually zero.

As of FY03, both batteries had reached an age where it was desirable to do more extensive monitoring of their condition and operation to determine whether life expectations were being met. Therefore, a contract was placed to continue monitoring battery performance at Vernon and begin a more formal tracking of operational data at Metlakatla. In addition, periodic postmortems of modules returned to GNB from both locations were resumed to assess how much degradation had occurred and estimate the remaining battery life. Previously, only cells from MP&L had been removed and returned to the lab for testing.

BESS Installed at the GNB Lead Recycling Center in Vernon, CA

Extensive electrical testing of 100A25 cell samples culled from the Metlakatla BESS was completed according to the designed test procedure. Results of capacity tests on the cells when they were cycled at an eight-hour rate to 1.75 volts per cell (VPC), as well as at other discharge rates, were included in the second quarter report for FY03. The cells continued to perform extremely well after six years in a partial charge application. Even at rates as high as one hour, compliance to the published capacity ratings was excellent.

During the third quarter of FY03, the outside test lab for the project (Clear Science) performed PbO_2 analysis, BET, XRD, and porosimetry tests, and sectioned and photographed grids and posts on cells from the Metlakatla battery system that were torn down in early April at our Fort Smith, AR manufacturing plant. A report on the postmortem analyses was received at the end of the quarter and was internally circulated at GNB Network Power Division of Exide Technologies for comments and review.

Twelve test cells were replaced in the Vernon BESS and shipped to Fort Smith for similar testing. A detailed test request was prepared for this teardown and analysis. An abstract was also submitted for consideration at the October EESAT conference for a paper that will include available data from the testing, tear down and analysis of the MP&L and Vernon cells.

Both the Metlakatla and Vernon batteries are nearing the end of their warranty period. A draft letter is being internally circulated regarding the future of the Vernon BESS. (The unit is wholly owned by GNB-Exide.) GNB-Exide will seek funding for repair and maintenance of the battery and electronics from internal and external sources. Similarly, George Hunt is preparing a proposal for replacement of the Metlakatla battery, which is wholly owned by the MP&L utility.

Fourth Quarter Status

Chemical analysis of active material and grid samples from the second teardown of the Metlakala batteries (after 73 months of service) showed that the cells are aging normally. Grid corrosion is averaging approximately 0.03 mm per year, which is less than typically found for an Absolyte battery under float conditions. This may be related to the fact that the battery is normally held at 80% SOC. X ray diffraction measurements of the positive active material show a high percentage of the β-PbO_2 that tends to be favored in cycling applications. Surface area measurements of the positive active material also show the expected trends for a battery that has been exercised in shallow cycles. Data on the negative electrode similarly indicate that the negative active material is also in good condition and is not heavily sulfated. In summary, the battery is aging normally for the type of environment it is in and appears to be on track to achieve its 8-year design life.

The electrical test and teardown data are being documented in a paper for the EESAT conference, which will be held in San Francisco at the end of October 2003. This presentation will include a summary of all electrical tests on cells from both the Vernon and Metlakatla facilities, as well as battery teardown analysis at two points in time for the Metlakatla battery. A teardown of cells removed from Vernon has been postponed until FY04.

Evaluation of Utility Scale System — TVA Monitoring

SNL Contact: Georgianne Peek
Contractor: Electrotek Concepts— Dan Sabin
FY03 Funding: FY02 Carryover Funds

Project Overview

TVA is constructing a large-scale, battery-like, power storage facility at Columbus Air Force Base, MS. The system will address power qual and relia issues assoc with the power transmission line and is designed to store electricity during off-peak periods, then retrieving it for use when the need for power increases. Using technology developed and provided by Regenesys™ Technologies Limited, of the United Kingdom, the plant is designed to store up to 120 megawatt-hours of energy and provide power for 10 hours.

Initiated in FY02, this ESS project is designed to provide data collection management, data and economic analyses, and dissemination of data on the performance of the Tennessee Valley Authority (TVA) Regenesys™ Electrical Energy Storage System in terms of its abilities to control power quality and reliability.

During the second quarter, a meeting to kick off the monitoring project was held at the TVA Regenesys plant site in Columbus, Mississippi.

The goals of the monitoring project are:

- To gather the data necessary to characterize the Regenesys system's operating characteristics from both technical and economic points of view in all modes. The entire system will be regarded as a black box power storage system.
- Evaluate the impact of the facility on power system operation, line loading, and capacity.
- Evaluate the impact of the facility on power system quality and reliability.
- Extrapolate the project results for future plants.

From the monitoring project and ensuing data analysis, TVA will learn:

- The value streams – which operating modes are more important and why (e.g. arbitrage, time shift, ancillary services, a combination, etc.);
- How well the plant performs while providing these various services; identify limitations and constraints;
- Availability and reliability of electricity;
- Overall plant efficiency of the Regenesys electrical energy storage system;
- Whether there is any degradation of the system;
- How energy storage might fit into standard elecgtricity market design;
- How Regenesys™ technology might be employed to augment intermittent renewable resources (e.g. wind, photovoltaics); and
- The attributes necessary for TVA to decide on when/where to deploy similar plants.

During the third quarter, Electroteck began creating a project plan for the data collection system and data analysis, which included setting up an electronic data collection site and working out firewall issues.

However, their project plan includes implementing lessons learned from the Regenesys system being installed in Great Britain, which has been delayed due to startup issues. In May, therefore, TVA decided to put the Regenesys project in Columbus on hold, with plans to restart in the October to December timeframe (first quarter of FY04).

Fourth Quarter Status

The project continued on hold during this quarter.

NAS™ Battery Demonstration Monitoring

SNL Contact: Georgianne Peek
Contractor: Gridwise Engineering– Ben Norris
FY03 Funding: $62.53K

Project Overview

The goal of this project is to obtain, analyze, and disseminate data on the performance of the Sodium Sulfur (NAS™) battery electrical energy storage system currently being installed at an American Electric Power (AEP) site, in Gahanna, OH, a suburb of Columbus.
The demonstration is composed of two NGK Insulators Ltd., NAS battery modules that will provide up to 500 kW of power quality protection for five minutes, plus 100 kW of peak shaving capacity for seven hours per day.

Sodium-Sulfur Battery

Operations to perform the data and economic analyses began in January 2003, under a contract with Gridwise.

The following March, the goals of the monitoring project were reviewed at a meeting among SNL, AEP, Gridwise Engineeringr, and Endecon Engineering. At that meeting, it was determined that Gridwise would perform a reliability analysis related to the power quality service, to include some indicator that reflects loss of life. The economic analysis was also expanded to include the power quality issues of peak shaving (customer and utility), spinning reserve, voltage support, and T&D deferral. Gridwise agreed to prepare their project plan based on the results of that meeting.

At the May During the progress meeting held in May 2003, Gridwise presented the plan for the data analysis portion of the project and the attendees decided that the plan should also include confirming operation of the unit during PQ events because of the difficulties in calculating the DC energy of PQ events, which would introduce some error into the overall DC energy calculations from the database.

Gridwise also presented the plan for the economic analysis. The attendees decided that the Gridwise economic analysis plan should use data from AEP customers of various classes in addition to the Gahanna site, plus data from two other meters in the Gahanna campus.

Later that month, SNL, Technology Insights, NGK, and Gridwise met and addressed the issue of monitoring loss of life. They decided that the mean value over the course of the discharge (or charge) would be the best measure for a methodology, based upon data from the database, to calculate the "mean internal resistance" for each cycle as a figure of merit for degradation.

At the May 2003 ESA meeting in Chicago, AEP reported on several problems concerning the operation of the NAS unit that arose during the second and third quarters of FY03, which have either been corrected or are in the process of being corrected (For details of those issues, see Quarterly Progress Report for Third Quarter, FY03).

Fourth Quarter Status

Gridwise presented the Preliminary Data Analysis and Economic Analysis Reports on 9/18/2003. The following is a summary of the preliminary reports.

During its operations at Gahanna, the NAS storage device has been operated in three different modes (see Table 1): A 175kW/1300kWh per cycle mode until the end of October 2002; an 88kW/620kWh mode (Regime 3) until mid-May 2003; and a 100kW/385kWh mode (Regime 1) from mid-May to Sept. 2003.

The peak battery bottom temperature was limited to approximately 350ºC until the latest operating mode started. Since mid-May 2003, the temperature has been limited to approximately 332ºC. This will allow higher power levels during PQ operation, but will shorten the life of the batteries. The single-line diagram of the AEP NAS Demonstration system is shown in Figure 1 below.

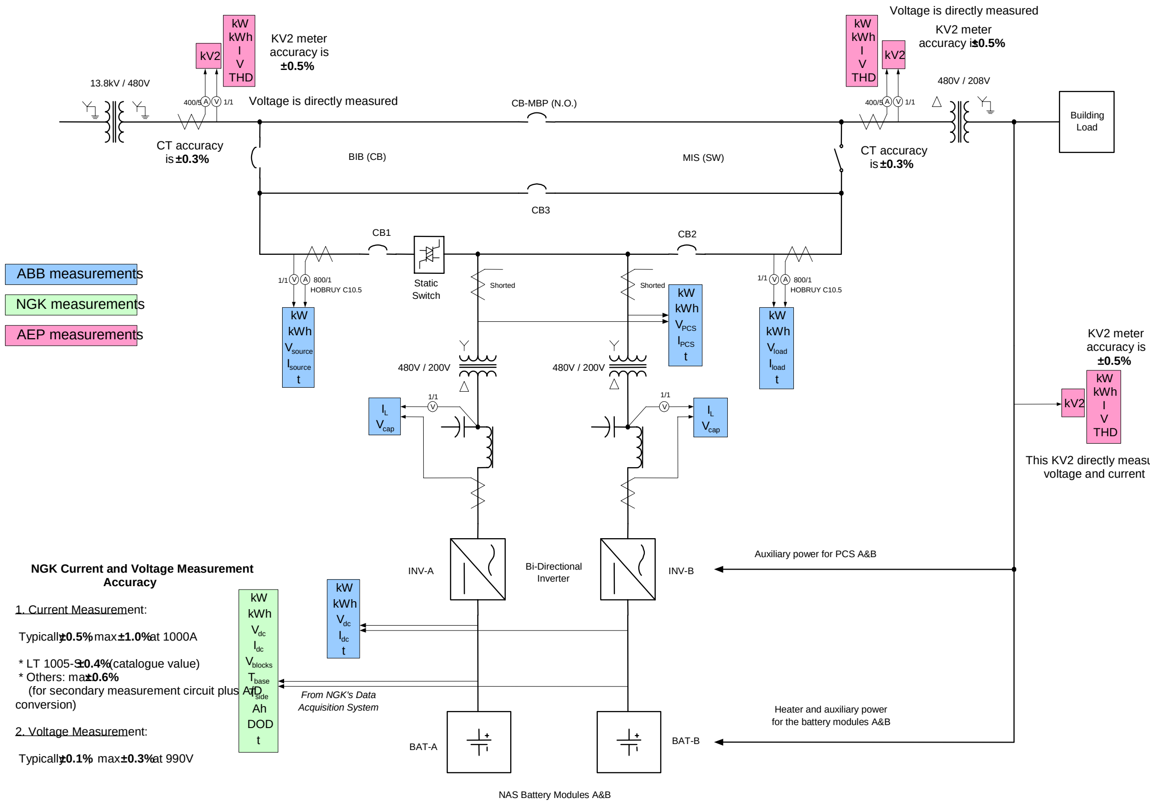


Figure 1. AEP NAS Demonstration Project One-Line Diagram

Some data anomalies remain to be investigated further, including an apparent calibration problem with the NGK data from battery 2, and some apparent discharging with insufficient corresponding charging. The power was adjusted in Regime 6 (90 kW) due to temperature excursions; but the vacuum setting was not adjusted, allowing greater heat loss. In addition, the DC measurement results are inconsistent with previously reported figures. Additional investigation is warranted.

Thus far in its operations, the principals have arrived at some preliminary conclusions about the NAS battery system. They include:

<u>Energy Shifting</u>

The NAS energy storage demonstration project has so far shown that it can implement energy shifting from nighttime to daytime while maintaining a reserve capability to provide full load support in the event of loss of grid.

<u>System Efficiency</u>

System efficiency is one way of identifying the cost of implementing displacing energy from off-peak to on-peak ours. The lower this efficiency is, the greater the cost differential between on and off peak times must be before the displacement can be economical. The auxiliary heating function reduces the efficiency significantly, even when the system is operating as designed; but when the energy displacement stops (as over the weekend), the auxiliary power continues while the charging costs cease. Unless additional insulation can be introduced, there might not be a simple way to reduce auxiliary power consumption.

Load power interruptions

Load power interruptions likely to cause disruption of operation have so far occurred with more frequency than similar grid power interruptions. AEP and ABB are continuing to identify potential improvements in design needed to resolve these interruptions.

NAS Operating Schedule

Finally, this analysis has shown that the NAS operating schedule will need to be adjusted in order to align it with on-peak intervals used by typical electric power tariffs. The adjustments to make will depend on which operating regime is used. When the NAS is operated at high energy displacement levels, some tariffs might limit the off-peak time to such an extent that the NAS cannot be charged during the off-peak time; therefore, not all combinations of operating regimes and tariffs will make sense. Doing this Adjusting the operating schedule will assure that either or both displaced energy and/ or peak load reductions will be maximized.

When the NAS is operated at high energy displacement levels, some tariffs might limit the off-peak time to such an extent that the NAS cannot be charged during the off-peak time; therefore, not all combinations of operating regimes and tariffs will make sense. See figures 2 and 3 for storage power flows.

Following is a list of items/ questions/ possible solutions discussed during the 9/18/ 2003 meeting:

1. The peak shaving period of *energy* and *power* modes does not match the load well, thereby negatively affecting the economics. The peak shaving period will be changed.
2. Quiescent voltage estimate.
3. Possible problems with differing definitions of a "cycle," as viewed by the principals. Cycle will be defined in a subsequent report.
4. DC resistance problems seem to be appearing. Need before data? Possible fix is to filter.
5. NAS current meters.

Table 1. NAS Operating Regimes Tested

Operating Regime	PQ Protection	PQ Factor	PQ Interval	PQ DC kWh per PQ interval per battery	PS DC kWh per battery[1]	# PS Cycles Over Life	Operated Interval
1	30s	5.0	1 hour	2.2	210	1500	5/2/03 to present
3	30s	3.0	1 hour	1.3	375	2500	Installation to 5/2/03

[1] Energy delivered from NAS battery during PS cycle.

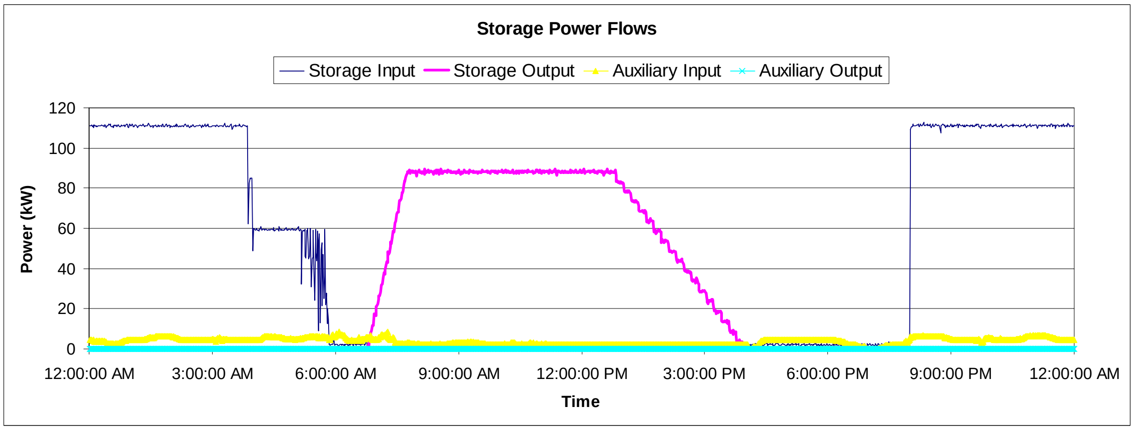


Figure 2: Regime 1 (after 5/2/03)

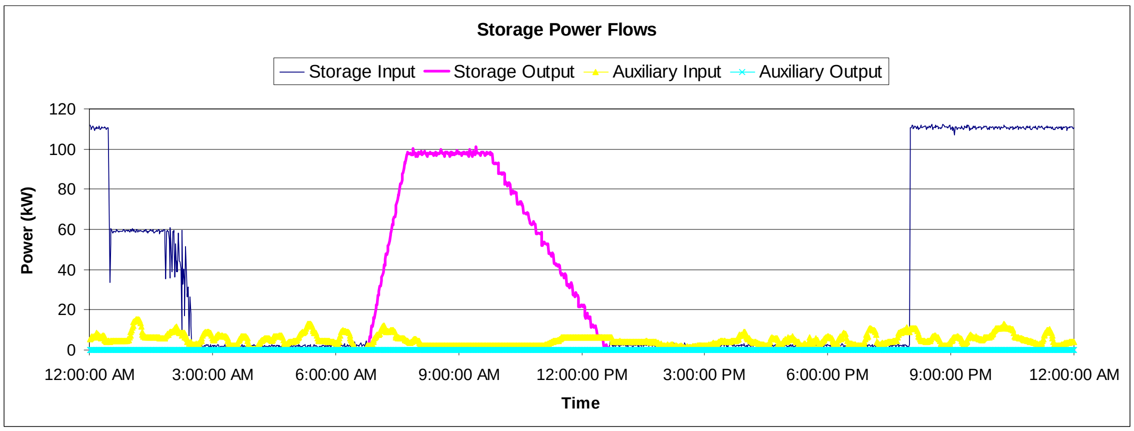


Figure 3. Regime 6

Alaska Battery/Diesel System Model

SNL Contact: David Trujillo
Contractor: Sentech — Rajat Sen
FY03 Funding: $93K

Project Overview

Alaska offers significant opportunities for the introduction of energy storage into distributed resource electricity supply systems. One such opportunity is in progress by the Alaskan Energy Authority (AEA). The two entities have developed a battery-diesel system model designed for reducing fuel consumption, increasing performance, and improving the rigor and reliability of power in remote Alaskan villages.

Provided for in a contract with Sentech, the model ("HybSim") concentrates on the feasibility of coupling battery energy storage systems with existing diesel generators (including photovoltaic hybrids in some cases) to evaluate different scenarios for using battery storage with small, stand-alone diesel generator sets (gensets). Modeling and analyses reveal that benefits can be gained from a storage-diesel system.

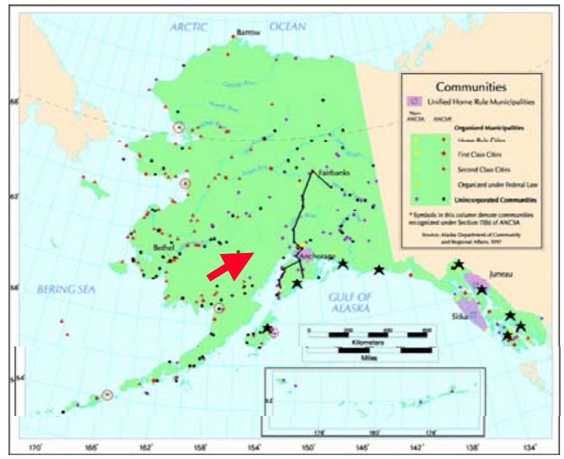


Figure 1. Site of Test Bed Solar/Diese/Battery System in a Remote Area of Alaska

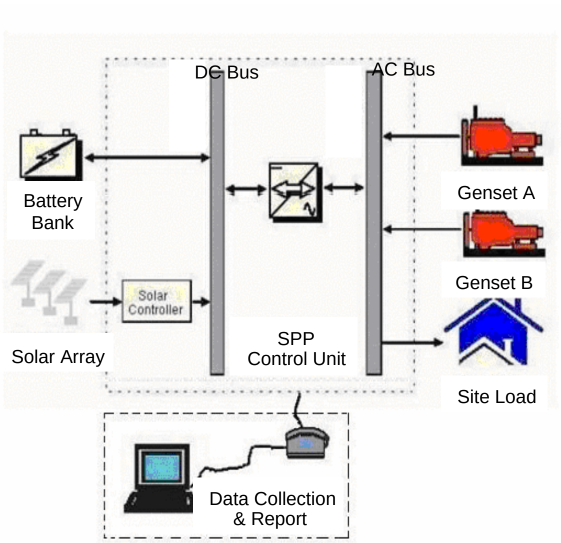


Fig. 2: Diagram of Model Solar/Diesel/Battery System

During FY01, HybSim was converted to modular code architecture (Fig. 2) and SNL provided technical and financial support to AEA for completion and installation of a photovoltaic (PV) system to an existing battery storage/diesel genset system in Lime Village, Alaska (See below: ***Alaska Battery/Diesel/PV-Hybrid Test Bed System (Lime Village)***. Based on analysis, SNL reasoned that data from this project would be beneficial not only for identifying power needs at Lime Village but also for validating HybSim.

Under a new contract with Sentech in FY02, PV analysis capability was incorporated into HybSim and the resulting performance validated. Upgrades and enhancements to the model were added and, under a new contract between Sandia and AEA in FY03, detailed feasibility studies were instituted, which would lead to the design, fabrication, installation, and testing of a prototype system during FY04. Code development was also completed and incorporated, which allowed Version 1 of the model to perform an analysis and determine an optimized system, to be incorporated into Version 2.

Testing and validation of Version 1 continued throughout FY03, which included technical performance of the model and user testing for feedback on ease of use with the interface. Additional PV capabilities were also incorporated and are undergoing continuous testing and validation. A user manual was incorporated into the software in the form of 'help' files. Final revision of the model's capabilities came close to completion during the previous quarter.

Plans were begun to provide a workshop on the model in Alaska for demonstrating the model and obtaining a list of willing beta testers for final model development and completion of Version 1.

Once all of the improvements have been thoroughly tested and validated, the model will be ready for application in identifying promising sites for hybrid system installations. It will also be available for interested parties to perform their own analyses and confirm the benefits of installing hybrid systems in other villages, as well as aid in sizing and configuring those systems.

The goal is to get the model into the hands of Alaskan agencies and establish a user base. We will then support the AEA by performing technical and economical analyses for system improvement for one to two village systems identified by the AEA. Plans also include full support of the annual AEA Energy Conference through participation and technical support of seminars.

With continued support and methodical effort, the model can become a viable tool for the Alaskan communities.

Fourth Quarter Status

In response to a failed battery system at the Lime Village Test Bed project, and in an effort to demonstrate the effectiveness of HybSim, the model tool was used to correctly analyze the technical and economical issues at Lime Village in an effort to determine an optimal replacement system. HybSim also analyzed power factor corrections, improved balanced loading, and inverter upgrade/corrections to maximize output and help optimize battery charging.

In addition to solving the problems with the LV Test Bed, HybSim demonstrated its value as a potential tool for technical and economic village analysis for local coops, the AEA, and power companies that own/manage village power systems.

A workshop on the HybSim Model was conducted on August 28, 2003. It was the first demonstration of the HybSim software to potential users in Alaska. The workshop was designed to commercialize the software product and establish a set of Alaskan users willing to participate in beta testing the model before release of "HybSim, Version 1."

Fourteen local Alaskan stakeholders in village systems attended, with four outside entities also represented. All participants commented very positively on the potential usefulness of the model in their own applications, and 70% of the local participants agreed to beta test the program.

Alaska Battery/Diesel/PV-Hybrid Test Bed System (Lime Village)

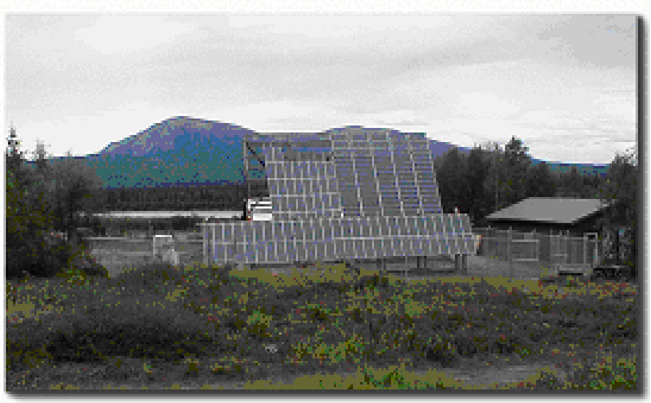
SNL Contact: David Trujillo
Contractor: Alaska Energy Authority (AEA) — Dennis Meiners
FY02 Funding: $67K

Project Overview

In concert with the results from a collaborative modeling effort (See**:** *Alaska Battery-Diesel Model System*, above), Sandia National Laboratories (SNL) and the AEA have agreed to install battery storage systems with small, stand-alone, distributed diesel generators (gensets) and photovoltaic (PV) arrays in a remote Alaskan community named Lime Village

Managed and funded by AEA, the Lime Village project is designed to both provide the community of Lime Village with reliable and affordable electricity and to validate the Battery/Diesel/PV model described above. Lime Village is a reconfiguration of the established prototype diesel-hybrid system. The system is coupled with an expanded PV array and a new, smaller diesel generator set that will provide the opportunity for collecting real time data on Alaskan Village hybrid systems for further modeling development and optimization of technical and market analysis.

The AEA believes the battery/diesel/PV approach will provide the community with optimal fuel savings and regards the potential success of this test-bed project as a model for expanding opportunities to other Alaskan villages with similar needs. McGrath Light and Power, on behalf of the Lime Village Traditional Council, will perform the actual construction, operations and management of the system.



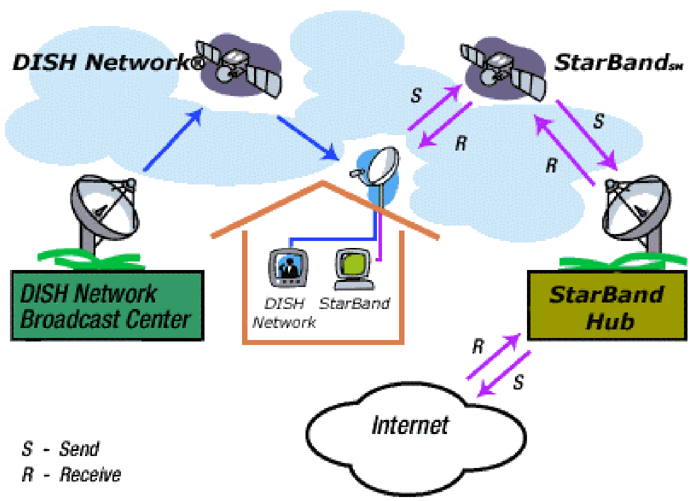
Lime Village Test-Bed: Typical Expanded Solar Array

Lime Village Test-Bed: Typical Diesel Generator

Technological and funding limitations had prevented the purchase of a suitable inverter and the development of a scheme for system integration. With the assistance of Sandia National Laboratories, however, all major system components, except the inverter, have been purchased and installed.

During FY02, a contract with McGrath Power and Light was put in place for the installation of sensors and meters and maintenance of Lime Village systems in support of test bed availability. Installation of some of the key meters and sensors was also completed.

A separate contract established data acquisition and reporting during the second quarter. A Starband Communications System (see illustration below) was installed, which provides the capability to transmit the test bed data to the Internet. Lime Villagers have been trained in the operation and maintenance of the system.



Data Transmission Using Starband Communications System

Under contract, and overseen by SNL and the AEA,UAF designed and installed a reliable data-retrieval interface for data transmission from the LV Test Bed that satisfies SNL requirements for the Lime Village project.

During FY03, fuel flow meters, a DC input and output current meters for each PV array were installed, which completes the majority of requirements to validate the Battery/Diesel/PV model.

The battery system in Lime Village began to fail during the first quarter of FY03. Therefore, negotiations began between AEA and McGrath to provide a replacement, with SNL offering technical support for specifications for the replacement system. Though we continue to work with the AEA for finalizing the Lime Village Test Bed, AEA has yet to provide a proposal to initiate the contract.

All sensors and meters were installed at Lime Village, but unavailable for data retrieval due to the failed battery system. This, in turn, impacted the inverter operation. As of the end of the third quarter, the village was operating on diesel only.

Fourth Quarter Status

Working jointly, SNL, Sentech Inc., the AEA, and McGrath Power and Light used the HybSim model as a tool to analyze the technical and economical issues surrounding the failed battery system at Lime Village. HybSim revealed solid approaches for resolving the Lime Village problems, such as power factor correction, improved balanced loading, inverter upgrade/corrections to maximize output and help optimize battery charging, and an optimal battery replacement system.

Once the inverter is upgraded and the batteries replaced, the inverter will be placed back into operation and data acquisition will begin.

Sub-System Development

High Power Semiconductor Switch Development for PCS

SNL contact: Stan Atcitty
Contractor: Virginia Tech — Dr. Alex Huang
FY03 Funding: $130K

Project Overview

This project with Virginia Tech began in April 1998. The overall objective was to develop advanced components for the Power Conversion Systems (PCS) used to connect an energy storage system to the grid. The project enabled Virginia Tech to demonstrate the Gen-1 ETO and the world's largest MOS controller power switch (ETO 6 kV/4kA) in 1999.

A 1 MVA PCS system using Gen-1 ETO (1 kA/4.5 kV) was subsequently developed and demonstrated at Virginia Tech using a two-level voltage source converter topology. In 2000-2001, leveraging with a grant from Tennessee Valley Authority (TVA), Gen-2 ETO was developed and implemented in a high power converter targeting TVA's application in dynamic voltage support. In FY02, collaboration between Virginia Tech and American Competitiveness Institute (ACI) enabled the demonstration of a manufacturable Gen-3 ETO. With the support of the DOE contract, the TVA power converter has also been upgraded to Gen-3 ETOs.

In the first quarter of FY03, Virginia Tech tested and evaluated the Gen-3 at 1000A, 2kV, 1 kHz in continuous operation mode. During the second quarter, a high frequency, high power burst mode test was conducted. In that test, the ETO successfully switched 12 pulses at 2500V DC bus, and up to 4000A with a 10 kHz switching frequency. The burst mode test proves that the ETO can survive in extremely high frequency and high power conditions, which is an important reflection of its over-load and fault condition capabilities. In addition, snubberless turn-off capability at 5000A of the ETO has been tested and evaluated; and the reliability and the life time of the ETO was improved by optimizing its capacitors. The concept of the was also developed in FY03.

Also during FY03, Virginia Tech developed the concept of the Gen-4 ETO and supported various ETO tests conducted at ACI and the Naval Surface Warfare Center (NSWC) in Philadelphia.

Fourth Quarter Status

<u>Development of the Gen-4 ETO prototype.</u>

The first prototype of the Gen-4 ETO was built based on the design proposed in the third quarter of FY03 (Figure 1).

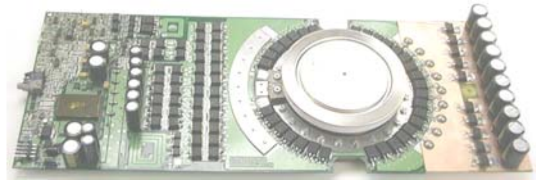


Figure 1. The prototype of the Gen-4 ETO

This prototype was modified based on the hardware of the Gen-3 ETO. Additional circuits are added to the Gen-3 ETO to obtain the Gen-4 function. The prototype is being tested and evaluated.

<u>Environmental test of the Gen-3 ETO</u>

During this quarter, Virginia Tech began environmental testing of Gen-3 ETO. The environmental reliability test is a very important step during the development of electronics products. Military Standard: MIL-STD-883E and Industry Standard (EIA-JEDEC): JESD22 are mainly used for the reliability analysis. Currently, two experiments, stabilization baking and temperature cycling, are being conducted. The thermal chamber used for these tests is shown in figure 2, together with the ETO devices. The ETOs successfully passed the 72 hour, high temperature stabilization baking test. More tests and analyses will be conducted during the first quarter of FY04.

Figure 2. Two Gen-3 ETO being tested in the thermal chamber

<u>Research on the failure mode of the ETO</u>

The failure mode for the power switch is very important for the system's reliability. In most cases, it's preferable that the device short out, as opposed to opening. To study the failure mode of the ETO, the simulation of the ETO failed in an H-bridge building block (HBBB) for STATCOM was firstly conducted. Using software, the ETO was simulated in an H-brdige building block configuration (HBBB) to show its failure characteristics. The simulation results are shown in figure 3.

The simulation results show that the peak fault current through the ETO reaches 60kA, and the $current^2 time$ (industry uses this to determine the surge current capability of conductors) is about $2\times10^6\,Ampers^2 Second$. To ensure that the ETO will short in its failure mode, the ETO's own $current^2 time$ rating should be higher than $2\times10^6\,Ampers^2 Second$.

The ETO consists of a GTO in series with parallel MOSFETs. The typical failure mode of a GTO is fail-short. Therefore, the ETO failure mode is determined by the MOSFET. To study the failure mode of the MOSFETs, a MOSFET failure mode test was conducted. In this test, a single MOSFET was turned on to discharge a cap bank. The discharge current is designed to be high enough to destroy the MOSFET. The test results are shown in figure 4. The test shows that the MOSFET will first fail-short; then it will fail open, if the energy is high enough. The test shows that the peak current of the MOSFET reaches 2500A. The $current^2 time$ to destroy the MOSFET open is about $2200A^2S$. Consider the number of the parallel MOSFETs for the ETO's emitter switch and the gate switch, the $current^2 time$ to destroy the ETO emitter switch open is about $1.012\times10^7\,A^2S$; the $current^2 time$ to destroy the ETO gate switch is about $2.5\times10^6\,A^2S$. From this calculation, a preliminary conclusion is that that the failure mode of the ETO in this HBBB is fail-short. More research and tests are being conducted to validate the calculations.

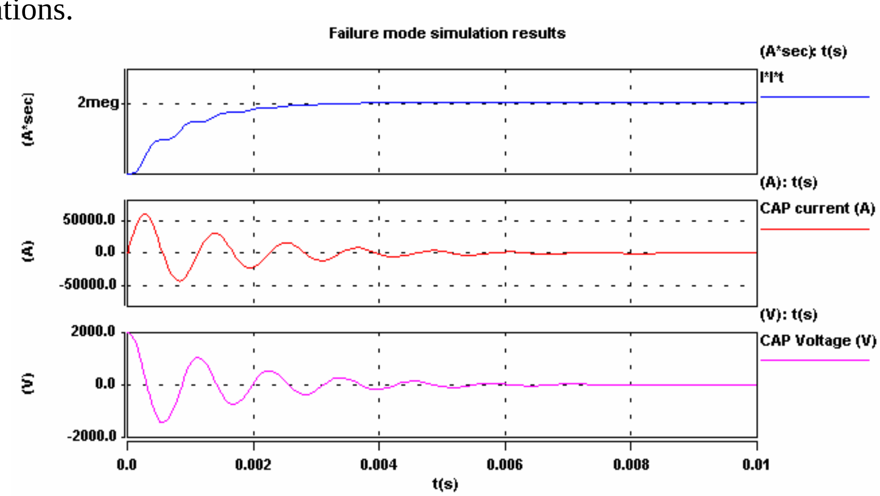


Figure 3. Failure mode simulation results

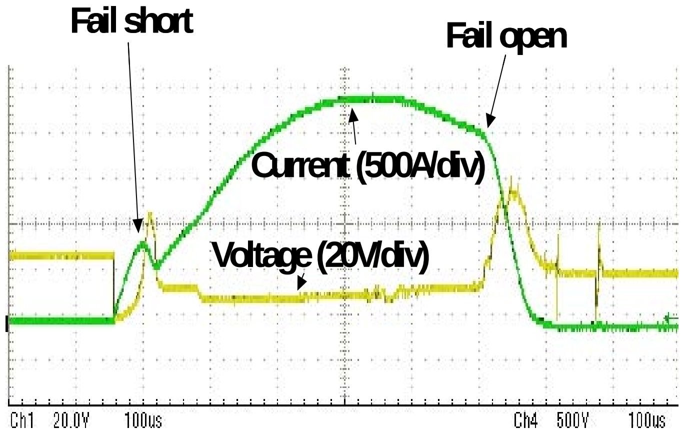


Figure 4. MOSFET failure mode test result

High Power Semiconductor Switch Performance Testing

SNL Contact: Stan Atcitty
Contractor: Naval Surface Warfare Center, Carderock Division
FY02 Funding: $105K
FY03 Funding: $20K

Project Overview

This is a joint effort among DOE, Sandia Labs, the US Navy, Virginia Polytechnic Institute, and the American Competitiveness Institute. The project is focused on subjecting a prototype power semiconductor device designated the Emitter Turn-off Thyristor (ETO) to a series of operational and environmental performance tests.

The device will be tested for a four (4) hour period at switching frequencies of 500Hz, and 1000Hz respectively, subject to a maximum junction temperature of ~ 115°C. The device will also be subjected to a one (1) hour thermal cycling test. A long-term environmental test to assess its operation and reliability at extreme conditions will also be conducted.

Figure 1- ETO Device

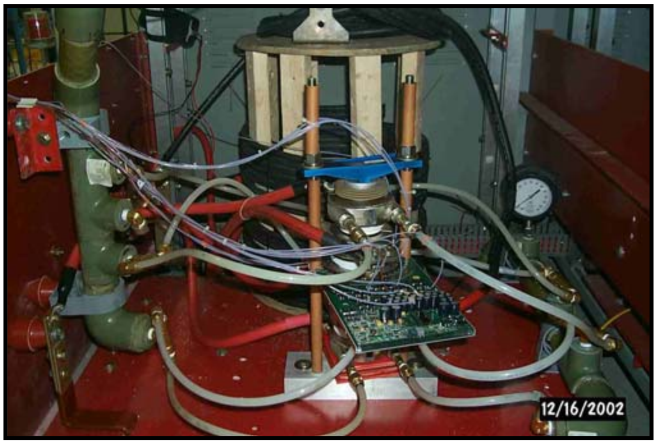


Figure 2- ETO Stack - Test Set-up

The project began in August 2002, and initial efforts through December 2002 involved identifying a suitable test location and modeling the test circuit, plus procuring, manufacturing, and installing the necessary circuit components. Test cabinets were installed and facility wiring modifications completed. Project personnel attended high voltage safety training, and test device #5 was installed and instrumented.

Full scale testing began in January 2003, but was halted due to an equipment failure and a safety mishap. Activities through March 2003 focused on remedial safety actions and test set-up upgrades required prior to re-testing. Activities through June 2003 included the start of re-testing and subsequent troubleshooting of the power supply, data acqusition system, and circuit components.

Fourth Quarter Status

Activities included completion of successful four (4) hour tests were successfully conduct at 500 and 1000 hz in early July. Figures 3 & 4 below illustrate representative waveforms of those tests.

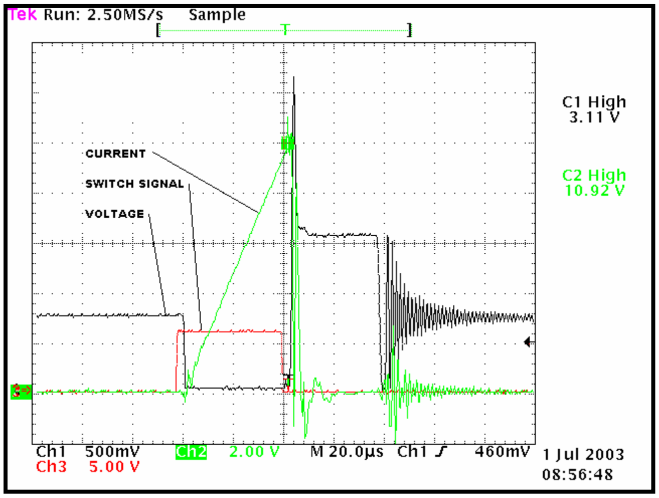


Figure 3. 4 Hrs @ 500Hz

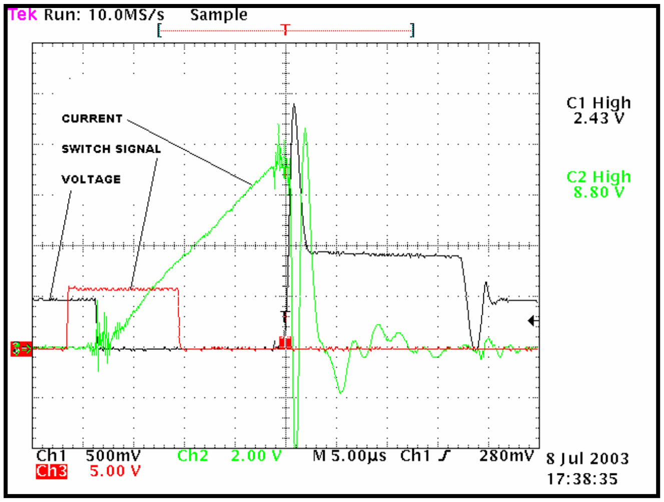


Figure 4- 4 Hrs @ 1000Hz

Subsequent testing during the remainder of July and early August was plagued by device failures caused by water-induced electrical shorts in the ETO stack. High atmospheric humidity caused rapid formation of condensation on the water-cooled heat sinks. These drops fell onto the stack components and caused electrical shorts in the ETO control board and GTO device. Much of this time was spent trying to lower the test cabinet humidity through the installation of air conditoning and de-humidification equipment. In addition, the test circuit and instrumentation were modified to eliminate the current and voltage waveform perturbations evident in the test results shown above. The output diode was replaced in an attempt to smooth the voltage waveform. The current waveform was smoothed by a supplemental snubber circuit.

ETOs damaged as a result of test equipment failures were forwarded to Virginia Tech for rework and repair. New GTO's were acquired and instrumented for the remaining test. Sixteen channels of thermo-couple measurements of selected ETO control board components (capacitors, FETS, diodes etc) were installed to monitor temperature changes in relation to switched voltage and current.

The final power cycle test was completed in late August. A graph of the anode and cathode temperatures from this test is provided in Figure 5 below.

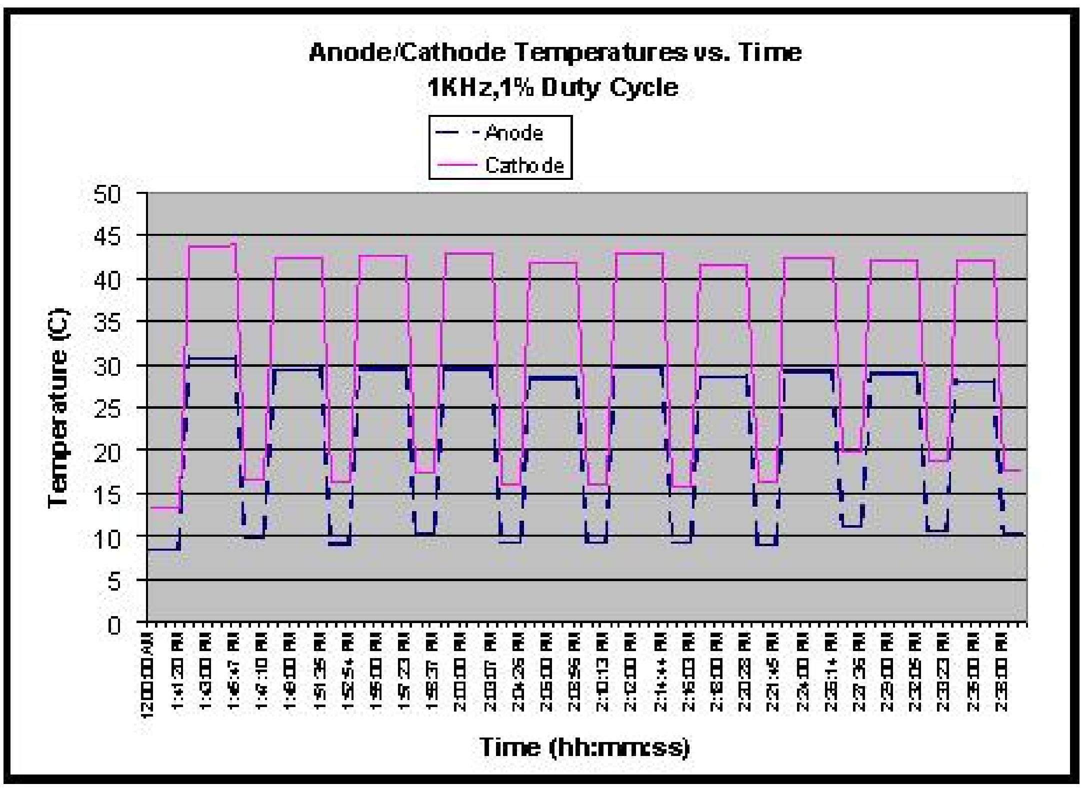


Figure 5

Completion of the one (1) hour power cycling test in August completed the ETO test regime.
Efforts in the next quarter will be to complete data analysis, complete the final test report, and present the test data at the EESAT conference.

Optically Isolated, HV/IGBT- Based, Megawatt, Cascaded Inverter Building Block For DER Applications

SNL Contact: Stan Atcitty
Contractor: Airak, Inc. – Mr. Paul G. Duncan
FY03 Funding: (note this is an SBIR project and not directly funded under ESSP)

Project Overview

Airak, Inc., in conjunction with the Center for Power Electronics Systems at Virginia Tech, has devloped the first optically isolated/interconnected, high-power cascaded inverter for Distributed Energy Resource applications based upon recent advances in optical sensors, optical interconnects, and High-Voltage Integrated Gate Bipolar Transistors.

Development of stackable topologies enables extremely high power systems to be realized, and when combined with optical voltage and current sensors, as well as optical control interfaces, enables a topology that greatly simplifies development within the high-power electronics environment.

The project has been split into two phases. The purpose of the Phase I effort, which administratively concluded in February 2002, was to develop a prototype of a single-phase, full-bridge megawatt inverter based upon newly available HV-IGBTs and combine these newly developed topologies with optical sensing, interfacing, and control. Design parameters concerning maximum voltages, currents, harmonics, and switching frequencies were developed and implemented, in conjunction with the latest developments in optically-based sensors and interconnects.

The current Phase II effort, which officially started in May 2002, is focused upon developing a three-phase version of the Phase I inverter system, and delivering the three-phase system to American Electric Power for testing and certification for grid-connect operations.

The following major milestones are anticipated for the fourth quarter of FY2003:
- Implementation of a new planar bus structure to improve thermal handling capability;
- Continued development of the control system;
- Redesign of the gate drive control system; and
- Implementation of the sensor monitoring system.

Fourth Quarter Status

Significant progress was made during this quarter in the development of the inverter controller, which is based on the Texas Instruments LF2407 digital signal processor. This processor was selected for several reasons: the peripherals required for inverter control are integrated into the chip; the chip has a good history of application for digital motor and inverter control; and it has a low cost. Test algorithms were written and successfully run on an LF2407 development module to verify its capabilities.

The inverter controller was designed as a modular unit based on the IEEE Std 1101.1 Card Rack Specification. The controller is broken into five separate functional units that allow for system configuration flexibility and ease of maintenance. Each functional unit is implemented on a pluggable Eurocard.

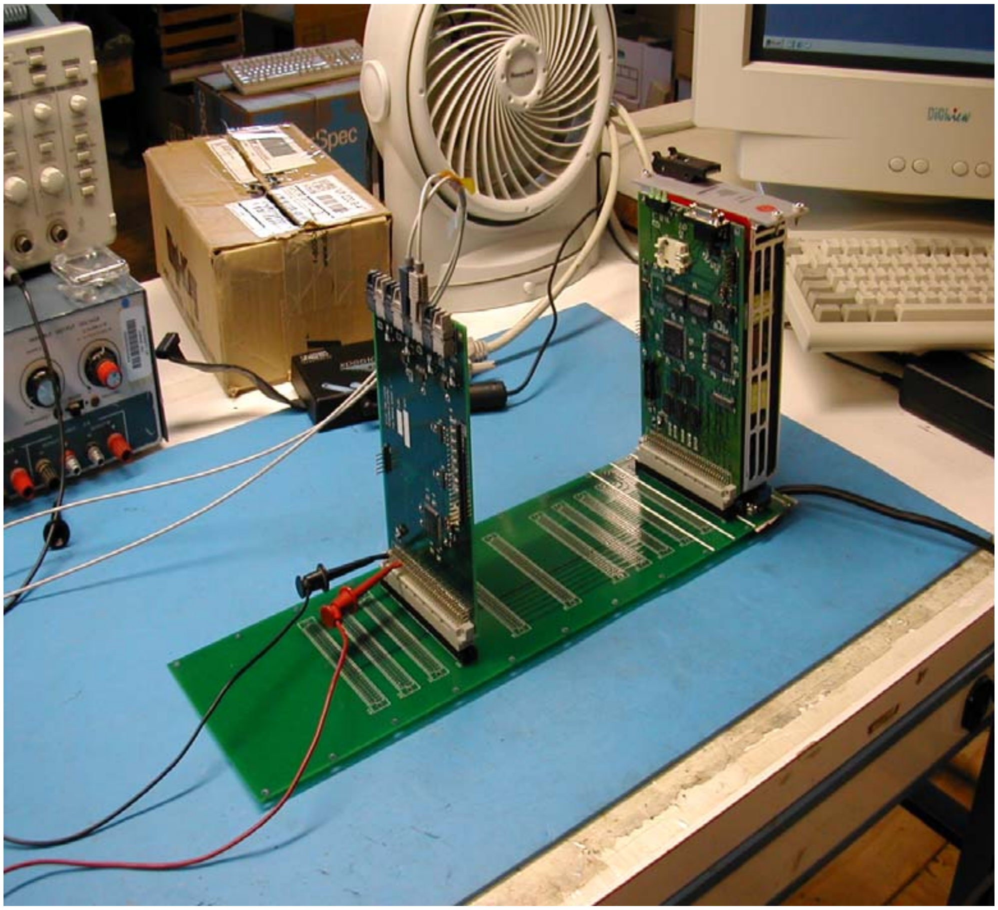


Figure 1. Optical gate drive interface (vertical left), eurocard backplane interface (flat against table), inverter PWM controller and hot-stackable power supply (vertical right).

The first functional unit consists of a commercially available, hot, swappable power supply that can be run in parallel with a second power supply, to increase system reliability. The second functional unit consists of an LF2407 DSP-based processor card that interfaces and controls the other cards in the rack. The third functional unit consists of a sensor input card that can accept either conventional sensory input or Airak's optical sensors. The fourth card consists of an optical interface board that connects the controller, through fiber optics, to the IGBT gate drives. Finally, the fifth functional unit provides digital input and output to sense contacts and drive relays for integrated system control.

The power supply, processor card, optical interface and the conventional sensor cards were implemented and currently undergoing tests. The following pictures show the hardware developed during this quarter.

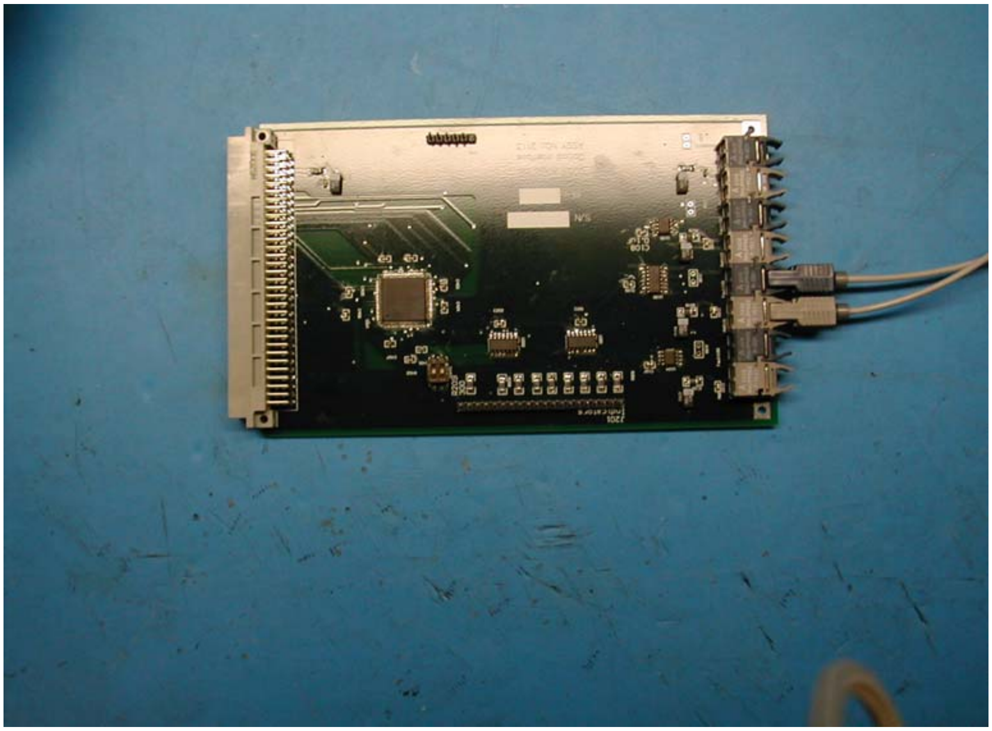


Figure 2. Optical gate drive

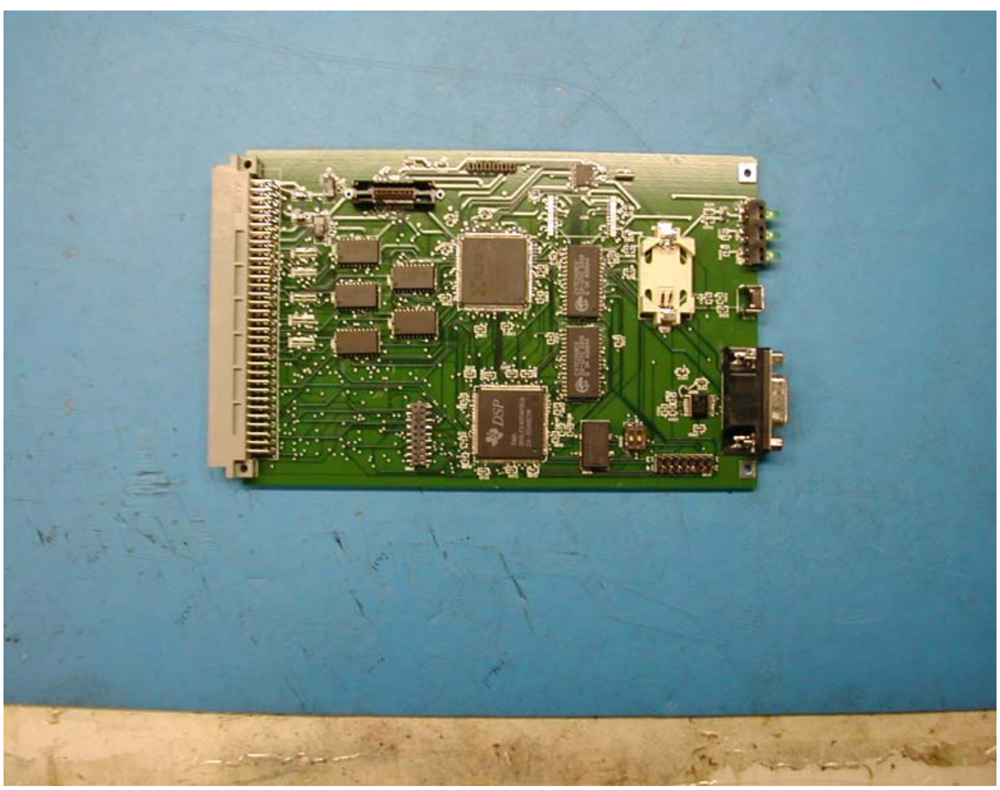


Figure 3. Inverter PWM

Bus-Bar Redesign

As reported in the third quarter report, the preliminary UPE board design was deemed inadequate with respect to thermal and load management and, as a result, a new board design has been successfully developed. The new design has been thoroughly modeled using Ansoft Maxwell 3D with respect to thermal analysis and electro-magnetic/electro-static propagation. Inductance/impedance analysis is currently being conducted and results are anticipated in time for EESAT03. Figure 4 shows the rendered CAD view of the busbar – the assembly is comprised of four, 0.25" sheets of copper separated by garolite G-10 insulation material.

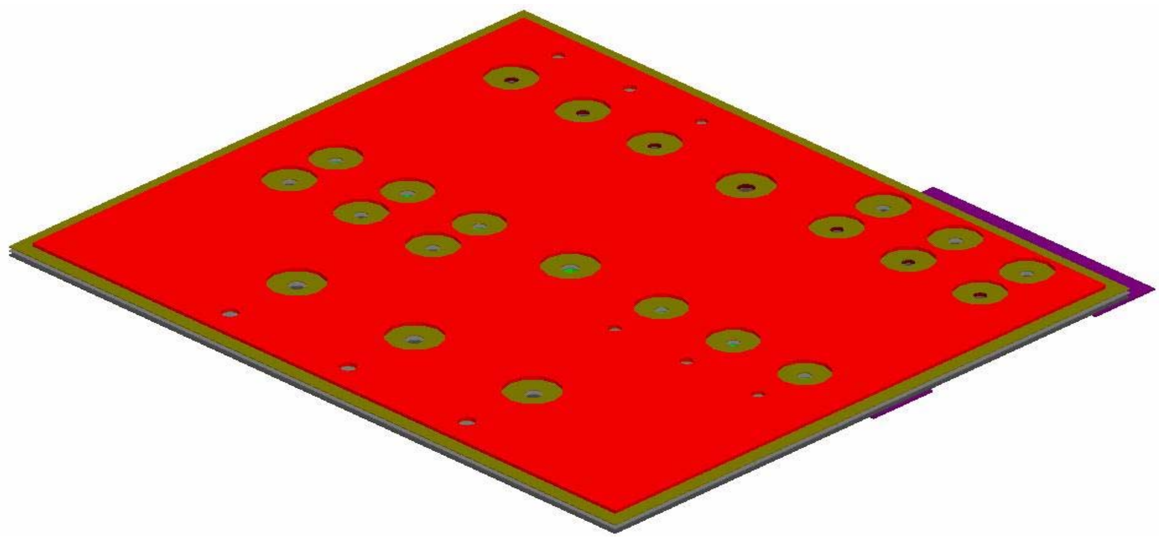


Figure 4. New bus-bar design.

Advanced Lead-Acid Battery Improvement Studies

SNL Contact: Paul Butler
Contractor: International Lead Zinc Research Organization (ILZRO) — Pat Moseley
FY03 Funding: $25K

Project Overview

Continued Research & Development (R&D) on Valve Regulated Lead-Acid (VRLA) battery technology is needed to improve operation, performance, and reliability in the field. This R&D project is a follow-on to the multi-year survey study that was completed in late FY02 on VRLA battery reliability.

The study concluded that there are many causes of the reliability problems experienced in the field, and that specific R&D on known areas for technology improvement is well justified. Such R&D is underway through the Advanced Lead-Acid Battery Consortium (ALABC) organization supported by ILZRO and the lead-acid battery industry. The ALABC has a well-rounded research program focused on key technical areas such as separator development, positive electrode improvement, case seal improvement, and charging optimization studies. The ALABC's total research budget of over $5M (for three-year scope) is heavily leveraged by a modest ESS investment.

The ALABC and its partners have been conducting extensive research that is geared towards improving the performance and enhancing the life of VRLA batteries. The areas of research, which have evolved over time and been recently updated, include:

(**Note**: One asterisk before a research area in the list indicates a project being summarized in this report; two asterisks signify currently active ALABC projects.)

- Application of catalytic and electrochemical recombination to VRLA batteries in cycling applications
- Design and test of an active equalization system for lead-acid batteries
- Novel techniques to ensure battery reliability in 42-V power nets for new generation automobiles
- Advancement of valve-regulated lead-acid battery technology for hybrid-electric and electric vehicles
- New electrodes for long life and power VRLA batteries in telecom backup and HEV applications
- Overcoming negative-plate capacity loss in VRLA batteries cycled under partial SOC duty
- Review of mechanistic aspects of oxygen cycle throughout the lifetime with emphasis on capacity fade in first 100 – 150 cycles
- *Influence of residual elements in lead and expander materials on the oxygen and/or hydrogen-gassing rates of lead-acid batteries
- Optimization of the positive plate of VRLA battery for EV/HEV
- Optimization of the structure of the positive grid-PAM interface
- RHOLAB-reliable highly optimized lead-acid battery

- Review of state-of-the-art of VRLA battery separator
- VRLA separator essentials
- Engineered separators for optimization of processing and performance in VRLA Batteries
- **Evaluation of different glass microfiber separators and membranes for VRLA batteries working high-rate partial state of charge (HRPSOC)
- **Separator systems for VRLA batteries in HRPSOC duty
- **Development of additives in negative active material to suppress sulfation during HRPSOC operation
- **Optimization of additives to the negative active material for the purpose of extending the life of VRLA batteries in HRPSOC operation
- **Optimization of the negative active material and PSOC cycle life of VRLA batteries for 42-V mild hybrid applications
- **Influence of trace elements on the performance of VRLA batteries at high temperatures and under HRPSOC

Fourth Quarter Status

The ALABC report titled "Influence of Residual Elements in Lead and Expander Materials on the Oxygen and/or Hydrogen Gassing Rates of Lead-Acid Batteries" was received in the fourth quarter of 2003. The following summary describes the key findings of this study.

The objective of this project is to improve the performance of VRLA batteries under float duty by controlling hydrogen and oxygen gassing at safe limits through re-specifying the 'acceptable' levels of residual elements in the lead used for oxide production. Sure knowledge of these limits will place less stringent demands on the refining of lead.

Raw lead materials contain many residual elements. With respect to setting 'safe' levels for these elements, each country has its own standard; but the majority of the present specifications for lead apply to flooded batteries that employ antimonial grids. In these batteries, the antimony in the positive and negative grids dominates the gassing characteristics so that the influence of residual elements is of little importance. This is, however, not the case for valve-regulated lead-acid (VRLA) batteries that use antimony-free grids and have limited sulfuric acid solution. Thus, it is necessary to specify 'acceptable' levels of residual elements in lead for the production of VRLA batteries.

In this study, seventeen elements were examined, namely: antimony, arsenic, bismuth, cadmium, chromium, cobalt, copper, germanium, iron, manganese, nickel, selenium, silver, tellurium, thallium, tin, and zinc. The following strategy was formulated to determine the acceptable levels:

1. Select a control oxide—an oxide of high purity used by many battery manufacturers in the USA;

2. Determine critical float, hydrogen and oxygen currents;

3. Establish a screening plan for the elements; and

4. Develop a statistical method for analysis of the experimental results.

The critical values of the float, hydrogen and oxygen currents were calculated from a field survey of battery failure data. The values serve as a base-line for comparison with the corresponding measured currents from cells using positive and negative plates produced either from the control oxide or from oxide doped with different levels of the seventeen elements in combination. The latter levels were determined by means of a screening plan that is based on the Plackett-Burman (statistical experiments tool used by chemists and engineers) experimental design.

Three concentration levels at which the measured float, hydrogen and oxygen currents were equal to their corresponding critical values were determined for each element. The lowest concentration value was taken as the maximum acceptable level (MAL). During this determination, synergistic effects between elements were found.

For hydrogen gassing, masking effects (‘beneficial synergistic effects’) arise mainly from the combined action of bismuth, cadmium, germanium, silver, and zinc. The combination of bismuth, silver and zinc gave the greatest suppression of hydrogen gassing; whereas nickel and selenium accelerated the gassing rate markedly. This indicates that nickel and selenium had a detrimental synergistic effect on hydrogen evolution. For oxygen gassing, the masking effects were due to the combined action of antimony and iron. Again, nickel and selenium were found to enhance the oxygen gassing rate; but the effect was not as strong as that observed for hydrogen evolution.

Two specifications were developed for the levels of the above seventeen elements in lead to be used in oxide production for VRLA technology; namely, specifications I and II. In specification I, beneficial elements, such as bismuth, cadmium, tin and zinc, were set at high levels. In specification II, these elements were at normal levels; i.e., the levels usually set in national standards to accommodate metal producers who do not wish to add such elements to their lead. Furthermore, the levels of most of the harmful elements (i.e., the remaining 13 elements) in specification I were twice as high as those in specification II.

It was demonstrated that VRLA cells using positive and negative plates produced from the control oxide and oxides with the two specifications exhibited satisfactory float, hydrogen and oxygen currents; i.e., below the corresponding critical values. Furthermore, these cells did not suffer from selective discharge of either negative or positive plates during float charging at a constant voltage. The charge voltage limit could be as low as 2.20 V, even when oxygen recombination had become very efficient.

The float currents delivered by the above VRLA cells were examined over a wide range of temperatures (21 to 62^{o}C). It was found that the effect of temperature on the float current of VRLA cells prepared from the control oxide and oxides with the two specifications increased in the order: specification I < control < specification II. Thus, by keeping beneficial elements at high levels, greater concentrations of harmful elements in lead could be tolerated. Importantly, the change in float current with the temperature of a VRLA cell using oxides with specification I was even smaller than that of a cell prepared with the control oxide.

In practice, VRLA cells are usually charged at a voltage limit between 2.20 and 2.45 V. In this voltage range, the negative-plate over potentials of cells using the control oxide and oxides with specification I or specification II were between –0.01 and –0.05 V at 21°C (Figure 1) and –0.01 and –0.1 V at 45°C (Figure 2). Furthermore, the oxygen-recombination efficiencies of the cells were very high (i.e., 95 to 97%). Thus, it could be concluded that, under prolonged float or normal charging conditions, these VRLA cells did not succumb to selective discharge of either the negative or the positive plates.

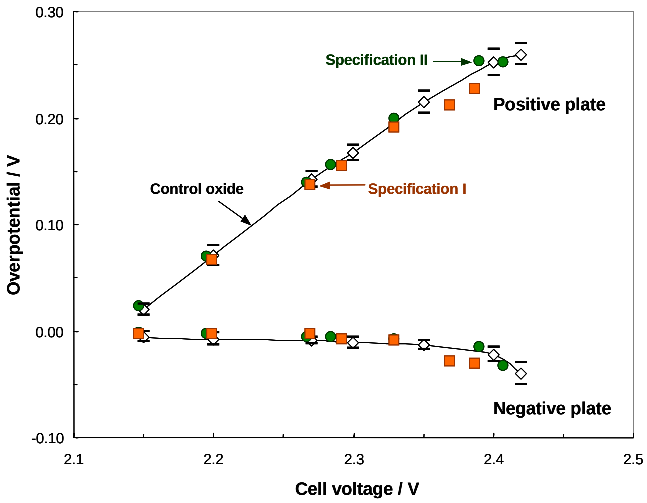


Figure 1. Change in negative-plate and positive-plate Overpotentials during overcharge at 21°C.

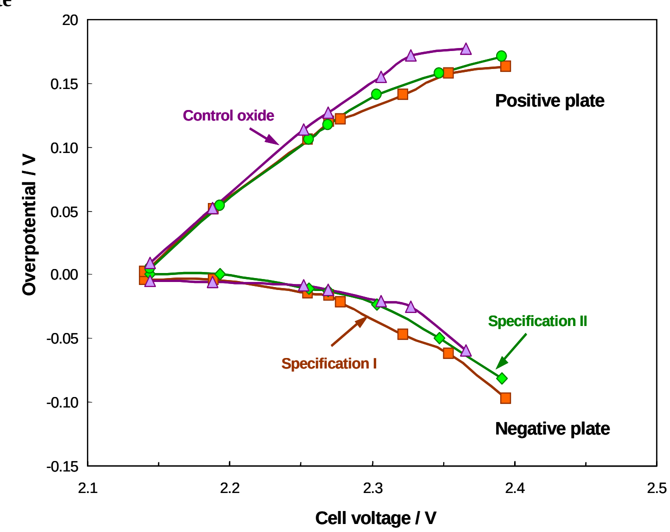


Figure 2. Change in negative-plate and positive-plate Overpotentials during overcharge at 45°C.

The change in float current with increasing temperature of VRLA cells using the control oxide and oxides with either specification I or specification II is shown in Figure 3. It was found that the float current increased with increased cell temperature. This applied to all cells irrespective of the type of oxide employed. Nevertheless, the cell using the oxide with specification I showed the lowest increase, and that using oxide with specification II displayed the greatest increase in float current with increased temperature.

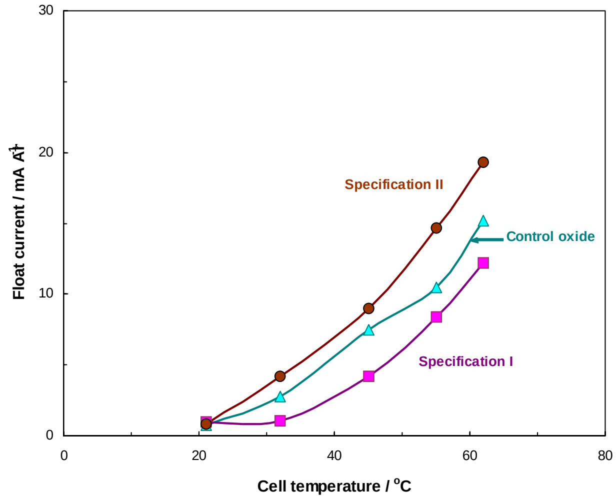


Figure 3. Effect of temperature on float current of VRLA cells made from different oxides.

In summary, the following progress was made towards the determination of 'safe' levels for the residual elements in lead used to produce oxides for VRLA batteries that operate in standby applications such as telecommunications and uninterruptible power supply systems.

- Synergistic effects have been found during the determination of the MALs of individual elements. For hydrogen gassing, masking effects ('beneficial synergistic effects') arose mainly from the combined action of bismuth, cadmium, germanium, silver, and zinc. A combination of bismuth, silver and zinc gave the greatest suppression of gassing, whereas nickel and selenium accelerated the gassing rate markedly. This indicated that nickel and selenium exerted a 'detrimental synergistic effect' on hydrogen evolution. For oxygen gassing, masking effects come from the combined action of antimony and iron. Again, nickel and selenium were found to enhance the oxygen gassing rate, but the effect was not as strong as that observed for hydrogen evolution.

- Two specifications — specification I and specification II — for the seventeen elements in lead have been developed through this systematic and thorough exercise. The beneficial elements were set at high levels in specification I, and at normal levels in specification II. Furthermore, the levels of most of the harmful elements in specification I were twice as high as those in specification II.

- VRLA cells using positive and negative plates produced from oxide with either specification I or II delivered satisfactory float, hydrogen and oxygen currents; i.e., within the corresponding critical values. Furthermore, these cells did not suffer from selective discharge of the negative or positive plates during float charging at constant voltage. The set voltage could be as low as 2.20 V, even when oxygen recombination had become very efficient.

- The float current of VRLA cells increased with increasing temperature, regardless of the oxide used. Nevertheless, the degree of increased float current was greater when using oxide with specification II than with specification I. This demonstrated that, by keeping the beneficial elements at high levels, greater concentration of harmful elements could be tolerated. Moreover, the effect of temperature on the float current delivered by oxide with specification I was even smaller than that observed for the control oxide that is presently used by many battery producers in the USA.

Therefore, the performance of VRLA cells prepared from oxides with these specifications was confirmed in terms of good charging ability and low float current. To determine the full advantages that might have been gained by using lead with the new specifications, it was recommended that the cycling ability should also be evaluated for VRLA cells prepared under the following oxide conditions, particularly at high temperature:

- Control oxide and oxides with specifications I and II.
- Oxide with harmful elements set at levels given in specification II, but with high concentrations of beneficial elements.
- Control oxide doped with beneficial elements at high levels.

Super Conducting Flywheel Development

SNL Contact: Nancy Clark
Contractor: Boeing — Arthur Day
FY03 Funding: FY02 Carryover Funds

Project Overview

The immediate goal of this project is to produce a 3- to 5-kWh flywheel energy storage system for use in a hybrid wind/diesel generation application. This project is the second part of a multi-phase design and development effort between the ESS program and Boeing to mature a new class of flywheel systems with multi-hour storage capabilities. It is being carried out in close conjunction with research into the development of superconducting bearing technology conducted under the Super Conductivity Partnership Initiative of the DOE Superconductivity Program. This research offers large potential benefits for future large flywheel systems in terms of system efficiency as well as capital and operating costs. The project has two primary objectives:

- Investigate a wide range of potential applications for advanced flywheels, leading to the design, fabrication, delivery, and site testing of an application-specific flywheel unit of 3 kWh capacity and a power output of at least 12 kW; and

- Develop the material, component, and system technologies that support building this demonstration unit while laying the foundation for long-term progress in flywheel energy storage.

To accomplish these objectives, the contract specifies the following six tasks:

Task1: Perform high-speed test and characterization of the low-cost rotor/bearing approach developed in FY00. For this approach, the system will store 1 kWh with a high safety factor at 24,000 rpm

Task 2: Down select from the candidate applications to a single target application.

Task 3: Develop a preliminary system design (including construction of a demo unit) for the chosen application.

Task 4: Develop a rim qualification plan and conduct supporting materials testing.

Task 5: Communicate program results and progress.

Task 6: Grow superconducting crystals and use them to construct an array for the demo unit's magnetic bearing. (This task was added to the original contract during FY02.)

Tasks 1 and 2 were completed during FY02. Work in the prior quarter, under Task 3, included exchanging data with the Alaska Energy Authority (AEA) regarding the desired direction for a field demonstration with a wind/diesel hybrid system. After reviewing the data, a 50-kW demonstration system was proposed. Work began to draft a joint Statement of Work for a possible field demonstration to take place in FY04. Additionally, the rim for the 5-kWh demonstration system was completed and delivered. During the third quarter, work under Task 4 included completion of the finite-element analysis (FEA) and rotor-dynamic modeling of the GS hub (an alternate hub design for the demonstration system). Results from these efforts showed excellent agreement with measured parameters from the 1-kWh flywheel tested last year and were favorable with respect to scaling to a 5-kWh system. Initial designs for a 5-kWh rim based on the GS concept were reviewed and the potential advantages of the GS concept explored. Additionally, difficulties with the C-ring test method for measuring rim radial strength were resolved and fiber composite fatigue strength investigations continued.

The most recent work under Task 5 included the presentation of one paper and continuing work on two others, in addition to ongoing participation in the group on Flywheel Rotor Safety and Longevity. Task 6 was completed in the second quarter of this year.

Fourth Quarter Status

Task 3

The offices of the Alaska Energy Authority (AEA) in Anchorage were visited in September. The project leader who had been working with Boeing on this task is no longer with AEA. Consequently, at this meeting, the Boeing system was introduced to the group leader and a copy of the system description document was left with him for routing within his group. A new project leader is being sought.

Statements of Work (SOWs) for a 50 kW motor/generator and a 50 kW motor/generator controller and rectifier were drafted. Both the motor/generator and the controller/rectifier are to be procured as part of FY04 work. The SOWs were sent to several vendors; but bidding is still in process.

The metal hub for the 5-kWh rim (delivered last quarter) was completed and delivered. As mentioned in earlier reports, the 5-kWh hub/rim design was based on a unit built for a parallel project, in order to take advantage of a previously demonstrated fabrication technique and to capitalize on an opportunity to reduce one-time tooling and material costs. The most attractive feature of the design is the solid hub connection, which makes the rotor virtually mode-free, because it is very stiff. Completion of the hub/rim assembly requires three press-fits, two between sections of the rim and one between the hub and the rim (actually a shrink-fit). The rotor is shown in Figure 1 during the final shrink fit.

Figure 1. 5-kWh hub and rim during final shrink/press fit operation.

The press and shrink fits were completed and the rim was trimmed to its final dimensions. The final fabrication step for the hub/rim assembly is to coat the rim with a clear resin to seal the fibers. After this step, a crack appeared on the inner diameter of the rotor at a point known to have high residual stresses. The crack did not go all the way through the rotor; but further analysis will be required to see how such a crack will affect operation, or to determine if there is a reliable repair process.

In subsequent discussions, the rim manufacturer indicated that the strength of the composite materials in the rim is lower at high temperatures, such as those that occur during the cure cycle for the coating. A similar rotor was built for another program earlier in the year using a slightly different assembly sequence and was successfully completed.

The 1-kWh flywheel tested last year uses a splined hub/rim connection that alleviates growth-matching and stress problems, and should allow for less-costly rim constructions. The top speed in previous tests (on a borrowed superconducting bearing) was 15,000 rpm, although the rim should have a comfortable safety margin for hoop burst even at 24,000 rpm. This quarter, the rotor, without the motor and magnets, was spun on a steel shaft with an air turbine system in an attempt to reach full speed and to gain more confidence in both rotor strength and dynamic stability.

Following horizontal balance, the rotor was mounted on the Toray Test Devices 3/8" air turbine, as shown in Figure 2. Sensors were located at the upper and lower extent of the composite rim, with data acquired throughout the run. Rotor imbalance during the run was minimal. At 19,560 rpm, oil slinging was observed on the monitoring video. The seal on the air turbine's lubrication system had failed catastrophically, completely depleting the oil in the system in less than one minute from the time the slinging started. The turbine brake air was supplied and the rotor brought to rest with no visually observable damage. The rotor was coated with oil (see Figure 3), but showed no evidence of a balance shift during the run, and no unexpected dynamics were observed. The test was terminated due to the turbine lubrication system failure.

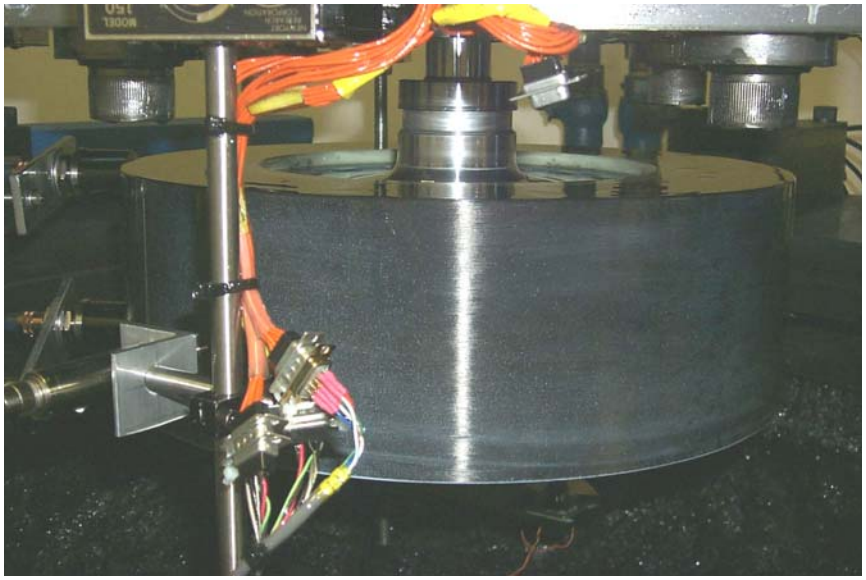


Figure 2. The 1-kWh rotor ready for testing. Cabling is for vibration sensors.

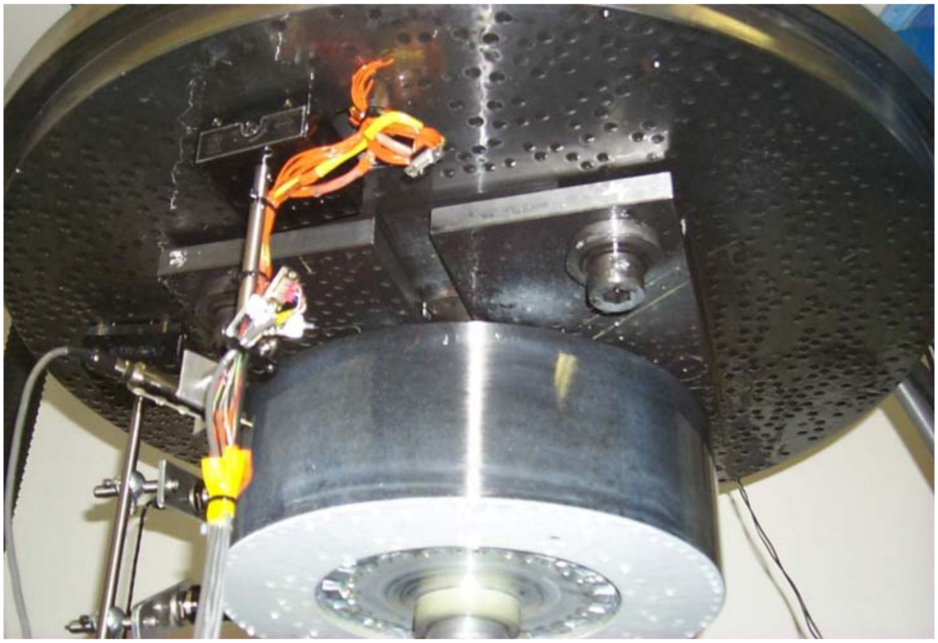


Figure 3. 1-kWh rotor after 19,560 rpm test. Results of the oil seal failure can be seen, but the rotor appears intact.

A new 6" × 9/16" quill tester has been commissioned at the Boeing test facility and will be used to finish the test sequence, if possible. The Boeing/Barbour Stockwell turbine uses a 9/16" quill that provides a much stiffer spin platform and a lubrication system that is unlikely to fail catastrophically, because the seal is designed specifically to provide sufficient lubrication during an emergency shutdown.

Task 4

Further analysis of the GS concept was brought to the point that it is now possible to estimate how the interface stiffness will scale with the part dimensions. The estimate was achieved through a combination of finite-element and closed-form analysis, as well as validation from the modal tap-testing described in the last report. The last report described an initial geometric and dynamic model for a 5-kWh Boeing/GS design. Without the scaling tools, that design appeared to have serious mode limitations at about 22,000 rpm, which would be within the expected operating range of the system. A revised design (see Figure 4) with only a modest increase in the spline dimensions now appears feasible from the dynamic standpoint, moving the critical mode speed out to 30,000 rpm, as shown in Figure 5.

Work continues at Penn State University to expand the knowledge base on fiber composite fatigue strength.

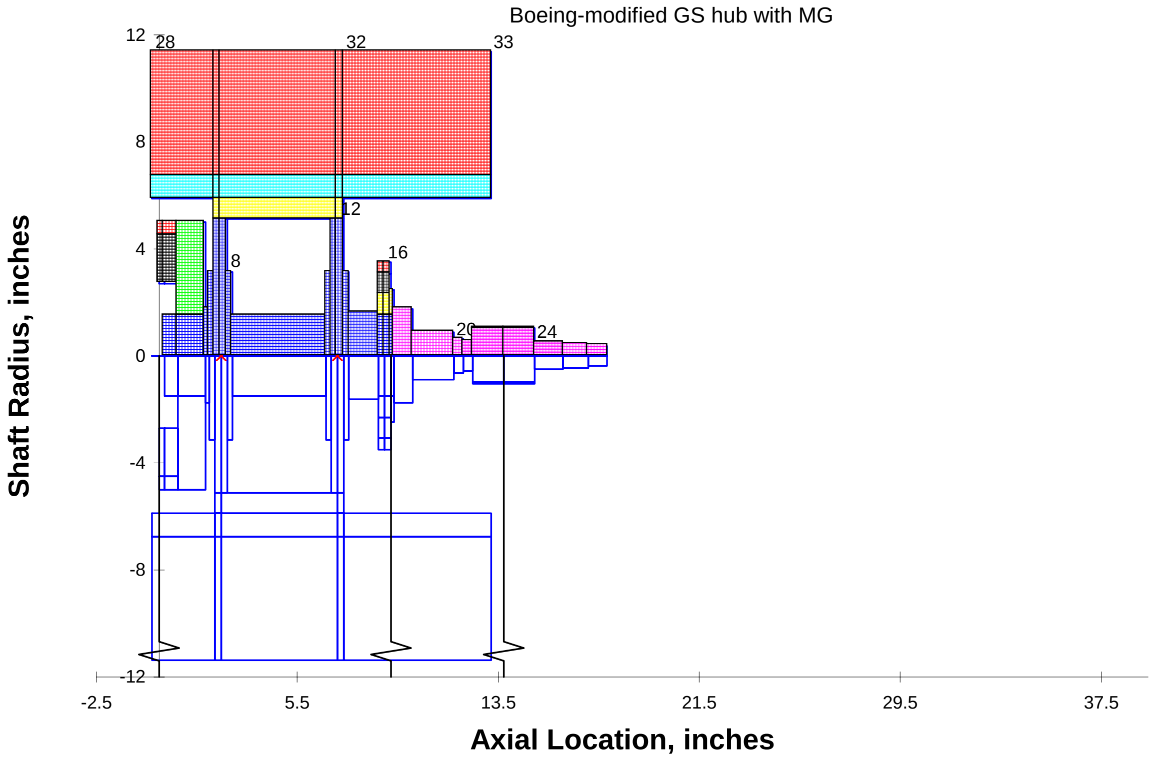


Figure 4. Geometry of an improved 5-kWh Boeing/GS flywheel design.

Trinity Project – Rotor Materials Tests for Flywheels

(Formerly: Trinity Flywheel Development)

SNL Contact: Nancy Clark
Contractor: Trinity — Melissa Redding
FY02 Funding: FY02 Carryover Funds

Project Overview

The ultimate goal for this technology is to develop a large flywheel system capable of storing 2kWh of useful energy, and the immediate goal is to scale up an existing flywheel system from 100 kW for 15 seconds to 240 kW for 30 seconds.

The project represents the first task in a proposed three-part scale-up effort proposed by AFS Trinity (a flywheel development company) and is part of a cooperative effort between the ESS, AFS Trinity, and the California Energy Commission. Initial model flywheel systems indicated that the materials used in the smaller system could not be used in larger systems. Work on this part of the project includes building the smaller flywheel system using new fiber, new matrix material, and a new manufacturing process. Once built, this smaller system would be burst-tested to determine the viability of using the new materials and manufacturing process to produce a larger system.

Early in FY03, problems were encountered while manufacturing rotors made from the new materials. It was determined that these rotors could not be mass produced using the rotor supplier's existing manufacturing processes. Later the rotor supplier determined that it would abe ble to reliably provide rotors only one-inch thick or less. Consequently, a new rotor was designed that made use of existing outer rims, but with two smaller rims (an 'intermediate' and an 'inner' rim) press-fitted together to form a new inner rim. Two complete rotors were successfully hand built using the new design for the inner rims, to be burst-tested during the fourth quarter.

The results of the burst testing will be used to create computer simulations of how the rotors will perform in a larger system. If the results of the simulations indicate that scale-up is possible, TCA and Trinity will investigate the options for mass producing the rotors.

Fourth Quarter Status

Two hand-made rotors (fabricated according to the new design) were delivered and burst tested. The results of the burst testing showed predominant success; the second rotor reaching a new performance record for rotors of this class. However, the testing was halted due to a significant increase in run out. The rotor was not destroyed by the test; but a hairline delamination crack was found in post-test inspection.

A third rotor was delivered and is scheduled for burst testing next quarter; and a fourth rotor was delivered, to be used to test a flywheel power system under a program funded by the U.S. Department of Transportation.

Delivery of the fifth rotor is expected in the next quarter.

Advanced Hybrid Controller and DGNode Follow-on Effort

SNL Contact: Garth Corey
Contractor: Intergrid Consulting — Rob Wills
FY03 Funding: $28.5K

Project Overview

Following the bankruptcy of AEI, much of the work on the AHC controller and DGNode was left unfinished. Completion of this work would lead to a completed and fully operational and documented AHC and DGNode. The original PI on the AES contract has the capability to complete the work still required on these items. All other follow-on work originally planned for the next phase with AEI has been abandoned at this time.

Therefore, a contract was placed with Intergrid Consulting (IC) to complete the commissioning of the AHC off-grid hybrid system at the DETL. Other deliverables, such as operating and maintenance manuals, were also included in the IC contract, with delivery still pending.

During the third quarter of FY03, the off-grid hybrid system and AHC were brought to operational status and data was collected. No further deliverables were forthcoming.

Fourth Quarter Status

As of the end of the quarter, the contractor had not completed the deliverables as required under the contract. No payments have been made to date, and none will be made until the full terms of the contract are met.

Energy Storage Test Systems

SNL Contact:	Tom Hund
Contractor	Team Specialty Products (TSP)
FY03 Funding:	$20K

Project Overview

The Power Source Engineering Dept. at Sandia has completed the initial upgrade to its test equipment to accommodate testing of a number of new energy storage devices such as Ultracapacitors and Nickel Metal Hydride batteries. A second contract has been placed with TSP to provide temperature control, plus additional programming to expand the range of the test system.

TSP was contracted to upgrade Sandia's Transistor Devices test equipment by:

1) Adding temperature control using the Tenny environmental temperature chamber,
2) Increasing system amperage to 500 amps,
3) Including a charge/discharge relay disconnect, and
4) Enhancing program performance.

Fourth Quarter Status

The contract with TSP was completed during this quarter. The Transistor Devices energy storage test system now is capable of high current (500A) low voltage (<48V) testing in an environmentally controlled chamber.

Nickel Metal Hydride Bipolar Battery Development

SNL Contact: David Ingersoll / Nancy Clark
Contractor: Electro Energy, Inc. (EEI) – Mike Eskra
FY03 Funding: (Carryover funds from FY02)

Project Overview

This is a direct, congressionally funded project that began late in the fourth quarter of FY2002.

Electro Energy, Inc. (EEI) has undertaken the development of a bipolar nickel metal hydride battery whose performance characteristics could meet a variety of energy storage application needs, including high voltage/high power modules having high cycle life.

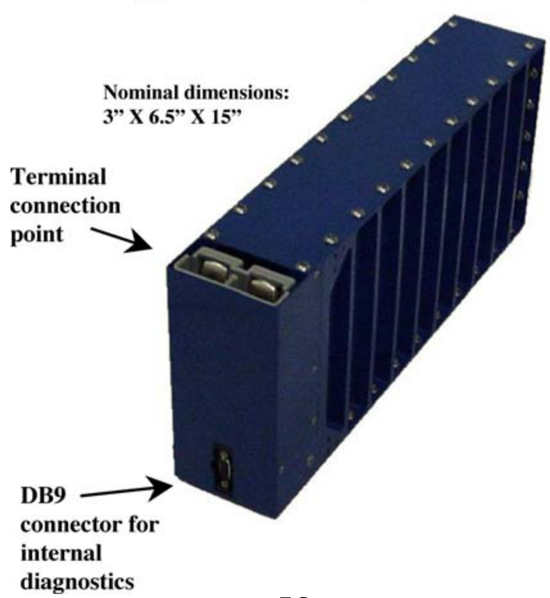
Initially, the goal of this one-year effort was to deliver a single, 50 V-module whose performance could be evaluated at Sandia National Laboratories (SNL) in an independent series of tests. The battery would have a nominal capacity of 6 Ah, and the cells capable of supporting 500 A constant current loads.

Because the testing hardware currently available at SNL is capable of supporting lower voltages at these high current levels, the specifications for the prototype hardware were altered to 40 V, which allows the battery to provide > 10 kW of power. An additional feature that will be included with the battery is charge/discharge protection circuitry to prevent the possibility of abuse conditions. The requirements for the additional circuitry include specifications limiting the voltage drop across the device to < 0.5 V during the high power loads.

Fourth Quarter Status

The 40 V prototype module was delivered to Sandia National Laboratories. The device has nominal dimensions of 3-inches x 6.5-inches x 15-inches (approximately the size of a shoe-box). The picture below shows the prototype, which is based on cells having nominal dimensions of 0.035-inch x 6-inch x 12-inch electrodes.

Prototype 40 V Ni-MH bipolar module



As illustrated, there are two primary connection points to the device including the primary power connection sized to carry large currents (in excess of 500 A), plus a DB9 connection for internal sensors packaged within the module. Although nominally a 40 V device, it is possible to add enough additional cells into this configuration to increase the nominal stack voltage to 50 V. Independent electrical characterization of the module will commence at Sandia National Laboratory in the first quarter of FY04.

During this quarter, Electro Energy participated in the DOE annual review and presented a current status report on the technical and programmatic aspects of its program. In addition, negotiations for the 2nd year statement of work have been completed, which includes a hardware deliverable.

NanoMaterial-Based Electrodes for Energy Storage Devices

SNL Contact:	David Ingersoll / Nancy Clark
Contractor:	NEI Corporation (*formerly* Nanopowder Enterprises, Inc.) – Dr. Amit Singhal
FY03 Funding:	(This is an SBIR project and not directly funded under the ESS program)

Project Overview

This SBIR activity focuses on new materials development and delivery of a laboratory prototype for energy storage systems.

A new area of materials research and development is centered on the preparation of nano-sized materials. A number of practical reasons exist for this interest, including the possibility of improved and/or enhanced materials properties that will ultimately impact device performance.

NEI Corporation is one of the companies that is involved in this new area of materials development, and they have identified candidate nano-materials that could significantly improve the performance characteristics of energy storage systems that utilize these materials. Toward this end, NEI has embarked on a program designed to prepare and evaluate the behavior of candidate nano-materials that will be used to fabricate a prototype asymmetric hybrid cell.

Cell Dimensions: 6" X 4"
(Courtesy Telcordia Technologies)

Fourth Quarter Status

In this quarter NEI participated in the annual DOE program review, and at that meeting gave an overview of its program and submitted a written report to be included in the proceedings volume. The presentation materials and proceeding report provide an overview of the entire activity, including a status of the program at that time.

Other activities occurring in this quarter include continued development of nano-composite $WO_{2,}$ as well as continued evaluation of the laboratory prototype, a picture of which is shown at right.

Strategic Analysis

PCS Magnetic and Functionality Analysis

SNL Contact: Stan Atcitty
Contractor: New Mexico State University (NMSU) — Dr. Satish J. Ranade
FY03 Funding: $7K

Project Overview

Since FY98, Dr. Ranade, on a consulting basis, has provided requested information, resources, and technical insights for interfacing electrical utility systems with energy storage systems. In FY98, Dr. Ranade participated in discussions on DC-AC inverter requirements and co-authored a report that summarized the state-of the art in power conversion systems for energy storage systems [1]. That report has been very well received in the Storage community. Subsequently, in FY99, his work focused on magnetics-related issues, since these represent a major cost center in power conversion systems.

During FY00-FY02, Dr. Ranade focused on issues related to Distributed Energy Resources (DER) and associated Power Conversion Systems (PCS). Specific topics addressed were the effect of motor starting on the operation of isolated DER, the modeling of DER in electric distribution systems, and the use of ultra-capacitor based energy storage systems. An Invention Disclosure for a device to improve transient loadability of DER has been filed based on this work, and prototypes of the device have been constructed under other projects.

In FY03 Dr. Ranade continued to provide technical assistance on a variety of topics requested by SNL; specifically, the use of ultra-capacitors and multi-level inverters. Dr. Ranade and Stan Atcitty of SNL also worked with Mr. Duff of PCCAP, Inc. Mr. Duff has demonstrated that biased electrolytic (Polarized or 'DC') capacitors ("anti-series" unit) can be connected back-to-back to create AC capacitors and has constructed several prototypes. These capacitors have been the focus of the work in the second and third quarters.

Fourth Quarter Status

Work continued on studying the back-to-back polarized capacitor scheme. Figure 1 shows a schematic of the anti-series ac capacitor constructed from polarized electrolytic capacitors. Figure 2 illustrates the capacitor voltage and current for an inductive load. As can be seen the voltage and current are ninety degrees out of phase and essentially undistorted.

Detailed tests were conducted to demonstrate that the 120/208 V, three-phase, back-to-back, biased capacitor scheme does, in fact, behave as an AC capacitor. As such, a polarized capacitor can be applied to motor starting and power factor correction. The potential benefit is a substantial volume and footprint reduction in AC applications. Additional studies will be needed to quantify losses and applicability at higher voltage/current ratings.

[1] Atcitty, S., Ranade, S., Gray-Fenner, A. " Summary of State-of-the-Art Power Conversion Systems for Energy Storage Applications", Sandia Report, SAND98-2019, September 1998.

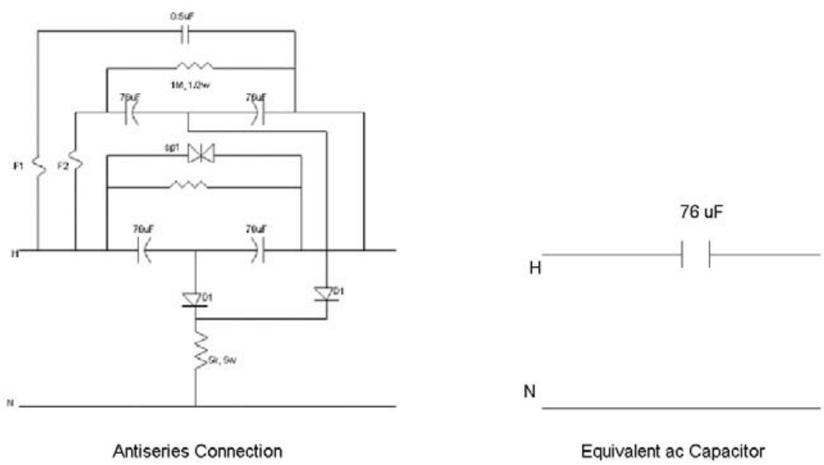


Figure 1. Schematic of anti-series connection showing polarized capacitor and biasing diodes.

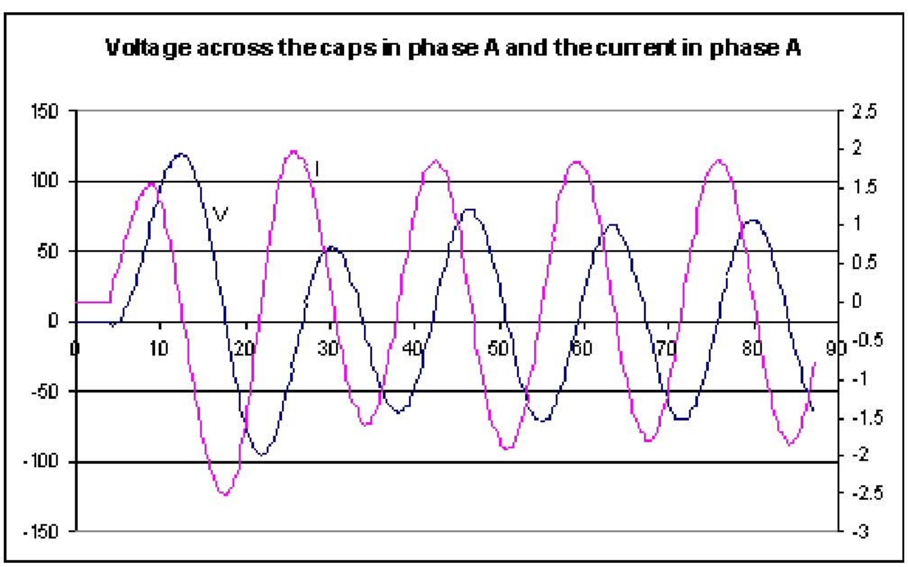


Figure 2 Capacitor voltage and current when energizing an inductive load

Short vs. Long-Term Energy Storage Technologies Assessment

SNL Contact: Paul Butler
Contractor: 122 West — Susan Schoenung
FY03: $100K

Project Overview

This assessment is a continuation of the study performed in FY99 (SAND2000-1550) that identified technology opportunities for both short and long duration applications of energy storage.

Based on the first study, the comparison of storage technologies with alternative options on a life-cycle cost basis was identified as needing further analysis. While first-cost considerations will commonly favor generation, life-cycle costs, including the impacts of environmental effects, might favor storage. A final report on this work was published in August 2003. A summary of this work appeared in quarterly reports prior to this publication.

A project kick-off meeting during the third quarter at Sandia National Laboratories (Livermore), clarified issues between ESS representatives and project engineers. Susan Schoenung, Bill Hassenzahl, and ESS staff also met briefly with Joe Iannucci of Distributed Utility Associates to discuss a proposed workshop on benefits and costs. Discussions included what this portion of the project will accomplish and who will participate.

Also during that quarter, life-cycle cost algorithms and the establishment of a list of parameters were begun for a sensitivity analysis to quantify the tradeoffs and comparisons using internal combustion generators fueled by a variety of sources, including natural gas, hydrogen, and diesel.

More detailed analyses and sensitivity calculations of the various technologies for the utility applications of storage defined in the Opportunities Analysis Phase 2 study are to be performed. The characteristics to be evaluated include energy density, power density, and duration of discharge and charge.

Table 1 below outlines the study's preliminary parameters; Table 2 defines the replacement assumptions for the various energy storage technologies.

Table 1. Parameters for Sensitivity Study

Parameter	Base Level	Low Level	High Level
Charging Electricity, ¢/kWh	5	2.5	10
Natural gas (for CAES), $/MMBTU	5	3.5	7
System life (levelization period), years	20	10	TBD
Discount rate, %	8.5	5	10
Carrying charge rate, %	12	10	15
Replacement costs	See table 2	Review for each technology	
Replacement period	See table 2	Review for each technology	
Shipping, taxes, import fees	none	Research for individual systems	

Table 2. Replacement Assumptions for Energy Storage Technologies

Technology	Replacement Period Years	Replacement Costs $/kWh
Lead-acid battery, flooded (bulk, DG)	6	150
Lead-acid battery, VRLA (bulk, DG)	5	200
PQ battery (lead-acid)	6	300
Ni/Cd (bulk, DG)	10	600
Regenesys	10	150 ($/kW)
Na/S (bulk)	10	230
Na/S (DG)	15	230
Zn/Br (bulk, DG)	8	100
Li-ion (DG, PQ)	10	500
V-redox (DG)	10	600
CAES, CAES-surface	30	0
Pumped hydro	30	0
High speed flywheel (DG, PQ)	20	0
High speed flywheel (PQ)	16	16,000
Low speed flywheel (PQ)	20	0
SMES (PQ)	20	0
Supercapacitors (PQ)	20	0
Hydrogen fuel cell (DG)	6	100 ($/kW)
Electrolyzer (DG)	6	50 ($/kW
Hydrogen engine (DG)	10	100 ($/kW)

Fourth Quarter Status

Applications of energy storage have a wide range of performance requirements. One important feature is discharge duration. The results of this study are based on energy storage technologies with a range of discharge capabilities.

As indicated in Figure 1, the first study compared technologies on the basis of a number of parameters, in particular: capital cost. Technologies have been further evaluated on the basis of life-cycle costs, which are expressed in annual $/kW. Current efforts are extending the analysis to examine sensitivity to various assumptions, including the cost of electricity. Although estimation of the benefits of electricity storage systems is critical to their implementation and use, that part of the equation is not included in this effort. The ESS program plans to consider the combinination of costs and benefits in a future workshop.

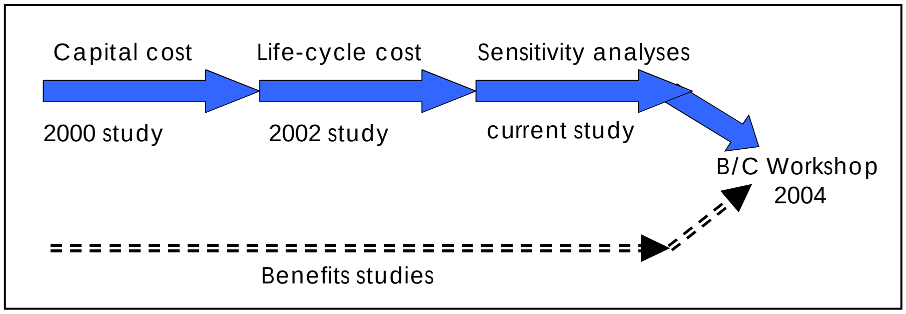


Figure 1. Progress of Comparative Studies of Energy Storage Technologies. (Cost analysis is being made consistent with other benefits studies for comparison in a Benefit/Cost workshop planned for 2004.)

The analysis of life-cycle costs has been performed for several application categories. These application categories include:

- bulk energy storage for large-scale load-leveling, with discharge durations of up to eight hours;
- distributed generation (DG) systems for peak shaving, with discharge durations from one to four hours; and
- power quality/end-use systems with a short a duration discharge of up to 30 seconds.

The technologies evaluated included:

- Batteries (conventional and advanced),
- Flywheels (low and high speed),
- Supercapacitors,
- Compressed air energy storage (CAES),
- Superconducting magnetic energy storage (SMES),
- Pumped hydro, and
- Hydrogen, primarily for use in fuel cells.

Earlier results have shown the importance of the hours of storage to the choice of most suitable technologies for a given application.

Life-cycle costs include not only the cost of capital, but also operation and maintenance (O&M), electricity and natural gas (for CAES), and replacement costs. Results are strongly dependent on the duration of storage discharge time, and also on replacement frequency and cost.

Results for the DG technologies scenario of four hours of full power from storage are given in Figure 2. The components of annual cost are indicated, including the capital carrying charge. The percentage shown in parentheses above each bar is the portion of the annual cost due to the capital carrying charge.

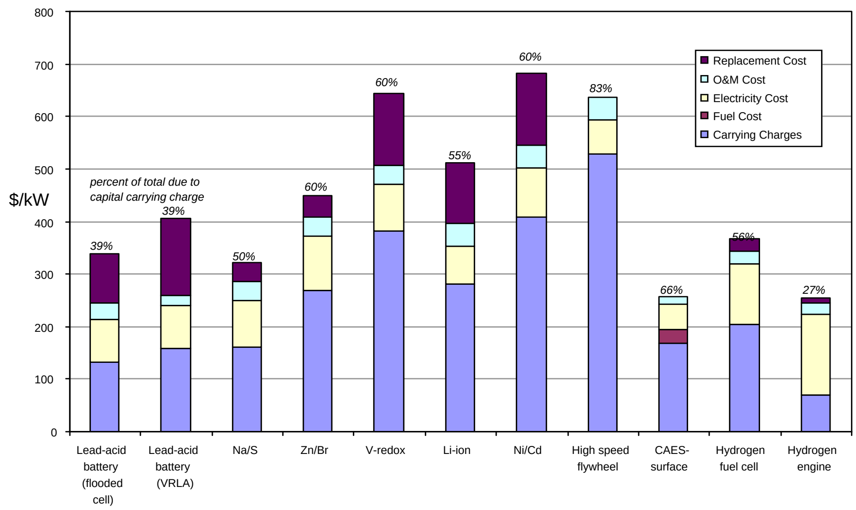


Figure 2. Components of Annual Cost ($/kW-yr) for 4-hr DG Systems.

Although the capital expense is always a major component, the fraction varies widely across the technologies. This result shows the importance of considering the full life-cycle cost when comparing technologies, not just capital cost.

Value of Storage for Restructured Utilities

SNL Contact: John Boyes/Paul Butler
Contractor: DUA — Joe Iannucci
FY03 Funding: $150K

Project Overview

This project is a continuation of a study initiated in 1998 (SAND2000-1550) that defined several possible electricity-provider scenarios for the use of energy storage following the restructuring of the U.S. electric utility industry.

In FY00-01, under Phase II of the study (Ref: SAND2003-0362), five of the most promising scenarios were selected as having the highest potential to make a substantial impact on the electricity delivery system: *Power Cost Volatility, T&D Benefits, Enhanced Environmental Externalities, Combined Heat and Power Output Smoothing, and Storage System Packaging Breakthroughs*.

During FY02-FY03 (Phase III), the economic benefits of energy storage were evaluated for a combined application involving arbitrage (buy-low, sell-high) plus Transmission & Distribution (T&D) deferral.

In addition to estimating the various financial expenditures and the value of electricity that could be realized in the marketplace, technical characteristics required for grid-connected distributed energy storage (DS) used for generation capacity deferral were also explored**.**

A draft of the Phase III report, titled "*Innovative Applications of Energy Storage In a Restructured Electricity Marketplace Phase III Final Report*" is under review. A statement of work for a Phase IV study has been drafted and a contract amendment negotiated with DUA.

Fourth Quarter Status

Phase IV began during this quarter. Following is an outline of the methodology and means by which the work will be accomplished.

T&D planning and operations are fundamentally a matter of uncertainty analysis, risk assessment and mitigation. To accomplish that, T&D planners need to understand and to explicitly account for the primary elements of risk – uncertainties. (Risk is expressed primarily in terms of financial values; though goodwill and reputation are also "at risk.")

Planners need to know the drivers and magnitude of the uncertainties, plus how to measure and mitigate their effects. The goal is reduced cost, including explicit inclusion of risk. Specific objectives include: optimizing capital budgets, optimizing capital returns and minimizing cost to ratepayers. It is within this context that storage must be weighed against traditional T&D upgrades (wires, transformers, etc.) and other emerging technologies such as distributed generation.

The following is an outline of the most important uncertainties leading to distribution planning risk. Some of these uncertainties are part of current T&D planning practices, while some would be unique to the use of storage in T&D systems.

Inherent Load Growth

- For a specific distribution (D) node: risk of stranded assets if that D node is overbuilt and expected loads do not materialize.
- If delaying an upgrade to a specific D node, and then demand growth exceeds anticipated magnitude, the unexpected demand on the D node causes overloading.
- For upgrade D node #1, there is opportunity cost: What if overloading then occurs on the "next best" upgrade, the one that would have been the next upgrade project funded (I.e., D node #2)?

Weather-related Peak Demand

- Important primarily for storage options.
- Demand that materializes beyond inherent load growth that is caused by unusual, but not rare, weather conditions.

Load Shape

- Primarily weather-driven (extreme temperature duration).
- Important primarily for storage options, though extended periods of "high" loading on transformers can affect the equipment's life significantly and can increase likelihood of its failure earlier than normal.
- For a specific D node, the load shape on the day(s) when load exceeds system rating requires more energy (hours) than the storage system can deliver.

Storage device reliability (important only for storage options)

- Storage must be reliable enough to truly mitigate the risk of its use in deferral applications.

T&D Planning-Related Risk – Current Utility Practice

Relating the uncertainties described above to the quantifiable risks mentioned below is one of the goals of this study. Quantification of risks associated with current practices for T&D planning is essential. Many of these risks are continuously assumed by distribution planners, but are not quantified.

The following section outlines the current areas of utility T&D planning, with an emphasis on how uncertainties and risks are addressed.

- The current risk-reward relationship of T&D planning; this addresses stakeholders, benefits "flows."

- Planning process.
- Budget process for distribution investments.
- Construction/capital budget reallocation.
- Operational contingencies.

The following figures (1 through 6) are example charts that show quantitative risk versus important uncertainty parameters. These figures will be adjusted as the specific results of this study are determined.

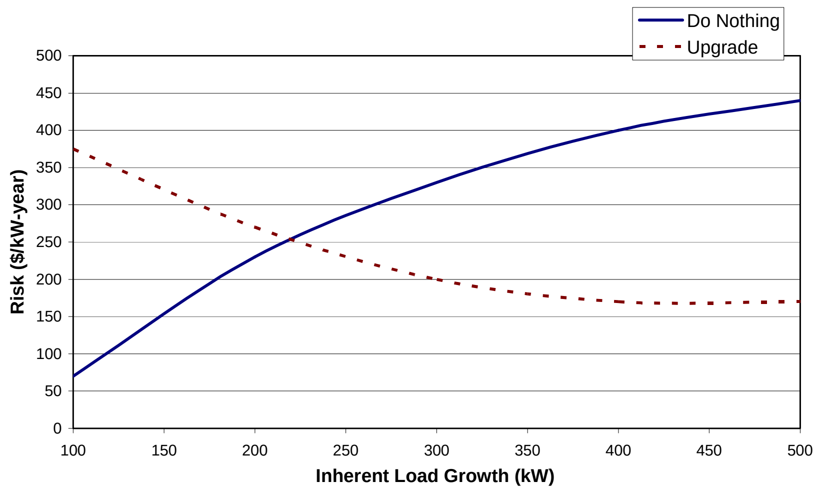


Figure 1. Load Growth Related Uncertainty.

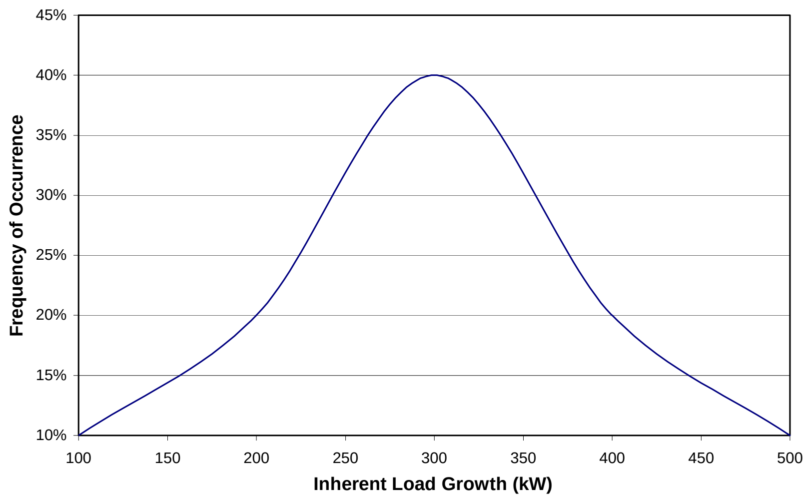


Figure 2. Inherent Load Growth Probability.

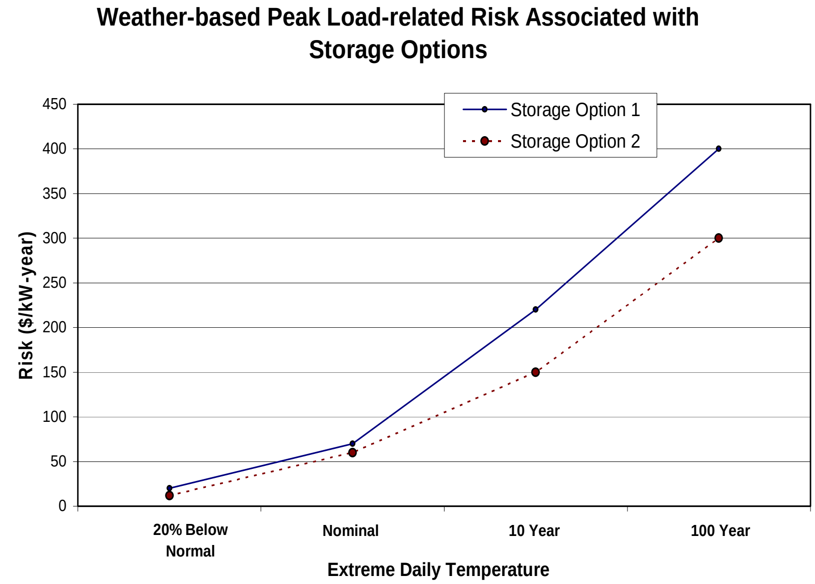


Figure 3. Risk Associated with Weather-related Peak Demand (in Excess of Inherent Load Growth).

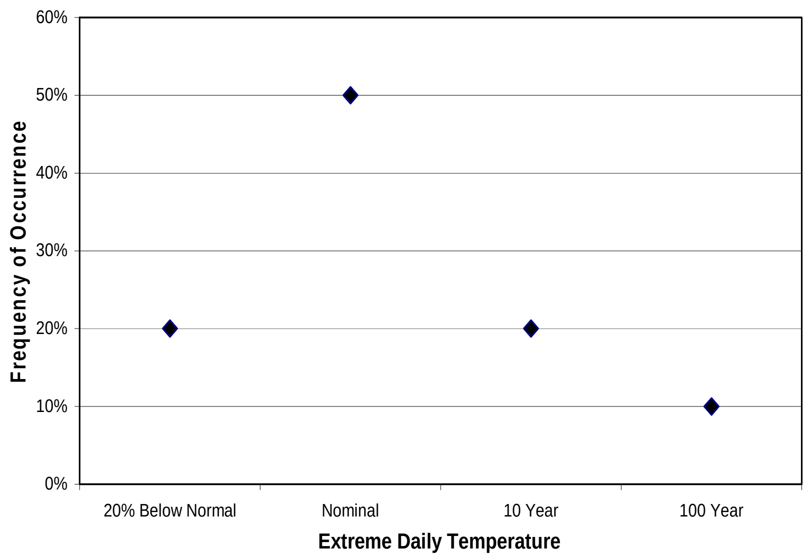


Figure 4. Extreme Daily Temperature Probability.

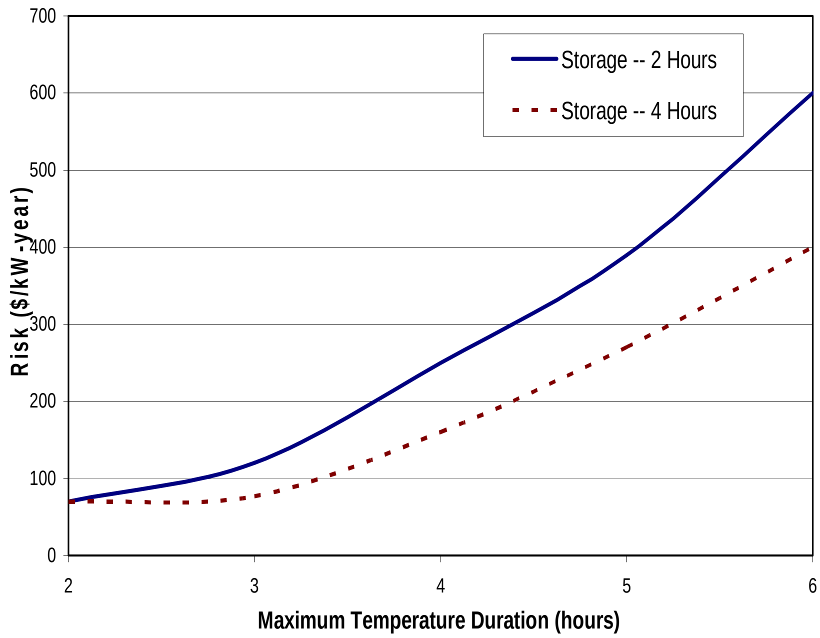


Figure 5. Risk Associated with Load Shape.

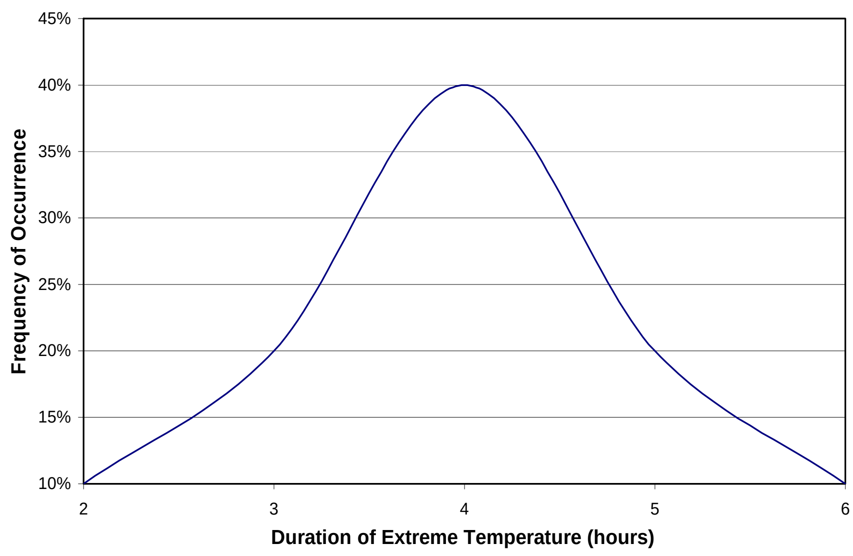


Figure 6. Load Shape Probability.

The use of storage as an innovative option for a T&D solution is outlined in the following topics.

- Improved risk-reward relationships for transmission and distribution planning
- Sizing issues (MW, MWh)
- Single year deferrals – quantifying/monetizing total risk
- Estimating risk-adjusted cost
- Redeployment annually
- Multi-year deferrals
- Hedging distribution peaks with a “roving” storage unit
- Ensuring distribution reliability metrics for performance-based ratemaking (PBR) purposes
- Optimization of returns on capital investments
- Attractive storage deployment tactics

The uncertainties of single and multiple year deferrals are presented in Figures 7, 8, 9.

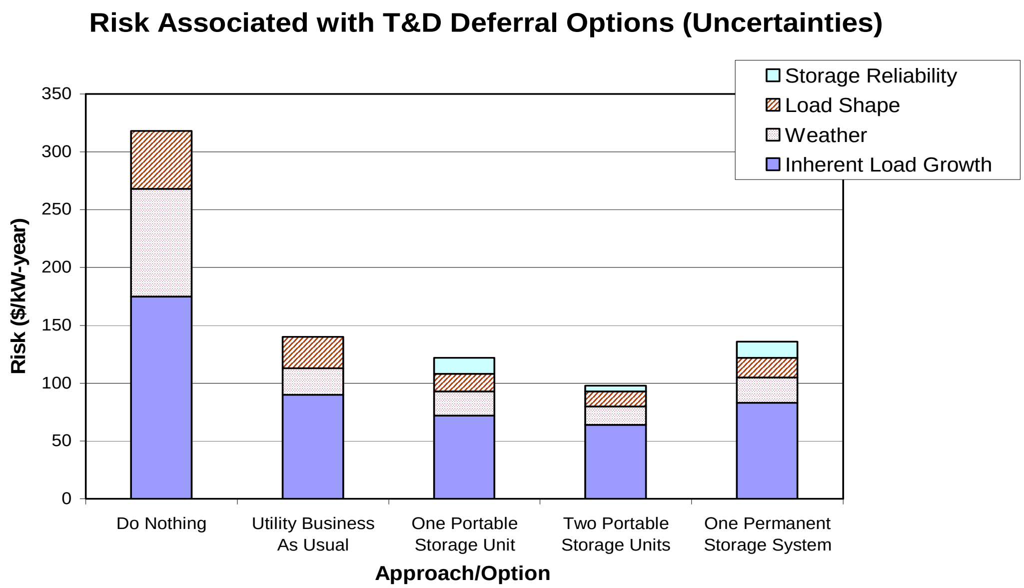


Figure 7. Risk Associated with Several Options.

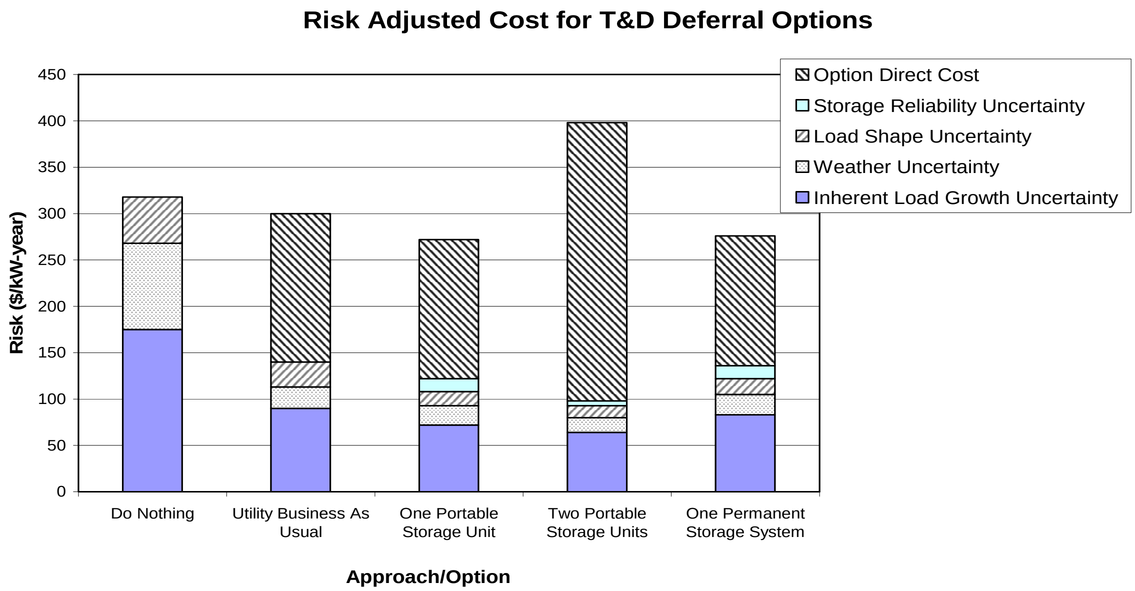


Figure 8. Risk Adjusted Total Cost.

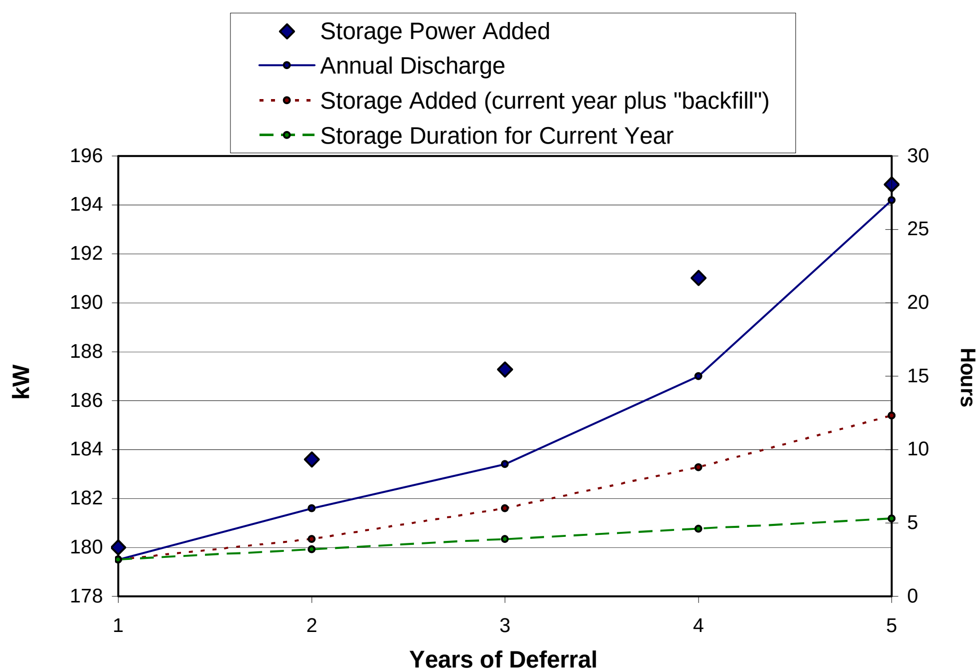


Figure 9. Effects of Multiple Year Deployment of Storage.

A storage system's apparent reliability is characterized by the following two categories.

- For a given site
- By way of diversity if using more than several units or if using N+1 units

Figure 10 provides storage reliability-related risk data for systems using one unit or two units.

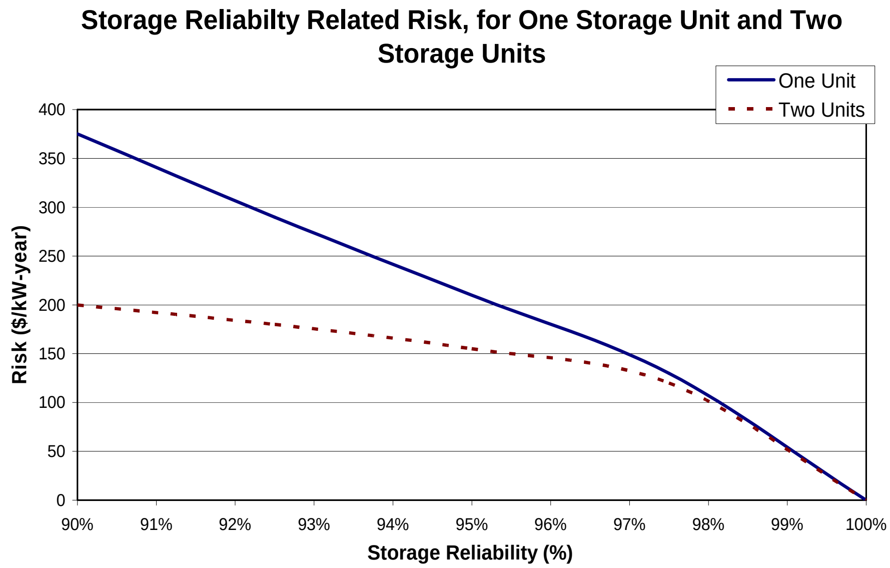


Figure 10. Risk Associated with Storage Capacity Redundancy.

EESAT2003 (Electric Energy Storage Applications and Technologies Conference)

SNL Contact: Nancy Clark

At EESAT 2002 the participants indicated overwhelmingly that they would prefer to attend EESAT 2003 at the same location. Therefore, the EESAT Committee will present EESAT 2003 in San Francisco, CA at the Sir Francis Drake Hotel on October 27 – 29, 2003.

The first call for papers was released in the second quarter, with a May 2003 deadline, and the deadline for submission of Extended Abstracts by the conference speakers was set for September 2, 2003.

Fourth Quarter Status

Preparations are proceeding on schedule.

ESS Web Site

SNL Contact: Georgianne Peek

The public access web site is continuing being updated to improve the availability of information to the public on Energy Storage Systems. The site resides on an external server located at Sandia National Laboratories. The web address is http://www.sandia.gov/ess/

California Energy Commission/DOE Energy Storage Initiative

SNL Contact: Garth Corey
Contractor: California Energy Commission (CEC) — Pramod Kulkarni
FY03 Funding: $150K

Project Overview

During FY02, the California Energy Commission (CEC) and the DOE formulated a plan for an energy storage initiative that would consist of up to six demonstrations of energy storage applications, to be sited in California. Funding of $5M has been provided by the CEC. The DOE ESS Program, through SNL, will provide expert technical consulting support for the project. The CEC will provide all administrative support for the project; while DOE/Sandia will provide all technical support.

The initial CEC/DOE Energy Storage Initiative Workshop was held at the Public Utility Commission in San Francisco, California on September 4, 2002. Approximately 20, personally invited utility industry representatives and customers attended to discuss the overall demonstration program and to help set the ground rules for the forthcoming Request for Proposal (RFP).

In the winter of 2003, a public meeting was held at the CEC offices in Sacramento to initiate a public discussion of the terms of the planned RFP. This meeting helped determine the final structure of the technical requirements of the RFP. Much of the activity during the third quarter of FY03 was related to the development and writing of the RFP at several meetings in Sacramento. The RFP is planned for release in late-July 2003.

It is anticipated that the final scoring of the proposals will be completed by early December 2003 and the first contracts will be placed by the CEC in the second quarter of FY04. After contract award, each demonstration will operate under CEC/DOE/SNL monitoring for up to three years.

Fourth Quarter Status

Following the issue of the RFP on July 31, 2003, the CEC received 14 "intent to bid" responses. A pre-bid conference was held at the CEC offices in Sacramento the following August 21. More than 50 persons attended the meeting, during which many aspects of the technical and administrative terms of the RFP were discussed. All bids are due to the CEC by October 20, 2003.

Economic Evaluation Support for CEC/DOE Energy Storage Initiative

SNL Contact: Garth Corey
Contractor: Distributed Utility Associates (DUA) — Joe Iannucci
FY03 Funding: FY02 Carryover Funds

Project Overview

Baseline economic metrics are needed for evaluating responses in support of the CEC/DOE Energy Storage Initiative RFP development activity (See above***: California Energy Commission (CEC)/DOE Energy Storage Initiative***). The metrics are to be developed in the form of a handbook prepared by an expert on the economics of energy storage systems.

Because of their expertise in the economics of utility and energy storage applications, DUA was selected to produce the handbook. Under the contract, DUA is providing expert economic consulting support and assisting the CEC/DOE team in evaluating the economic benefits of projects proposed for the CEC/DOE Initiative.

The final draft of the handbook, which was delivered to SNL in late May and appended to the CEC RFP as Attachment 14, is written for general use throughout the United States and contains an appendix specific to the economics of California. The handbook provides bidders for the CEC/DOE Energy Storage Initiative with a standard evaluation system for developing their economic analyses.

The final version of the handbook is to be published and distributed as an SNL SAND report in early FY04 under a new contract that will be placed in FY04.

Fourth Quarter Status

Following the completion of the California Handbook, RFP Attachment 14, there was no additional work remaining on this contract; therefore,no activity in the fourth quarter.

United States Coast Guard, National Distress System, Electric Power System Optimization Study

SNL Contact: Garth Corey
Contractor: US Coast Guard — CDR Pete Basil
FY03 Funding: $138K

Project Overview

This is the first Department of Homeland Security WFO effort to be managed by Sandia. The project originated during the second quarter of FY03 as a Sandia National Laboratories (Sandia), Work For Others (WFO) "funds-in" program that is being cost-shared by the ESS Program.

For the past several years, Sandia has worked closely with the US Coast Guard (USCG) to assist them in improving battery systems management in the electric power systems currently in use at remote sites in the National Distress System (NDS). Recent developments at Sandia in the optimization of system management techniques for parallel battery strings have the potential to significantly improve battery performance and life expectancy for batteries used in the NDS power systems.

The USCG accepted a proposal from Sandia National Laboratories Distributed Energy Test Laboratory (DETL) to study and evaluate the expected increase in performance of the NDS power system. This study will compare the performance results of two identical NDS power systems, one operated in its original configuration and the second operated under the control of an advanced battery management system developed by Sandia National Laboratories. The cost share portion of this project for the DOE ESS Program is the management and operational analysis of the two systems.

Final design of the facility to be installed at the DETL was completed during the third quarter of FY03 and the DETL ordered all hardware needed for the project. The batteries were delivered during this time, and the propane system, which cleared all ES&H reviews, will be installed late in the fourth quarter. The generators and controls are scheduled for delivery in late September to mid-October, and the ACONF unit is scheduled for delivery in early October. Commissioning of both systems is expected for mid-November.

Fourth Quarter Status

Final preparation and wiring of the NDS test set-up were completed in this quarter. Primary components of the data acquisition system were installed and readied for calibration following final installation of the gensets. The propane system was installed and prepared for hook-up to the gensets. System commissioning is expected as scheduled.

VRLA Battery Life Study

SNL Contacts: Rudy Jungst, Angel Urbina
Contractor: High Power Research Laboratory (HPRL) – Bor Yann Liaw
FY03 Funding: $100K

Project Overview

Valve-regulated lead-acid (VRLA) battery life prediction continues to be problematical and its failure modes are not well understood, particularly by the user community. The inability to predict battery failures has led to a situation in back up power applications wherein costly inspections and performance monitoring must be performed frequently to verify system readiness in case a utility power outage occurs. This situation is especially troublesome given that one of the expected benefits of a VRLA battery system is reduced maintenance cost.

The goal of this study is to develop a model of VRLA battery life for use in float applications. The model could be used to predict battery failures so that maintenance and replacements could be furnished in a timely manner. The intent is to be able to anticipate cell failures far enough in advance that replacements can be put in place before battery down time is actually incurred.

In this study, appropriately, measurable battery characteristics are being selected and related to float life through advanced mathematical modeling. In addition, fuzzy logic techniques are being applied to determine the relationship of battery use profiles, battery characteristics, and battery failure mode patterns to float life.

The general approach is to first survey existing battery life data and augment it with additional test data, as needed. Inductive models, such as artificial neural networks (ANNs), are then constructed using the battery properties that are most strongly correlated with float life. The models are adaptive and can, therefore, be easily refined as more data become available or as additional field experience is accumulated.

Initial work focused on developing a practical capability to model VRLA battery performance and degradation. A review of recent literature revealed that an equivalent-circuit, diagram-based approach might be promising; although, it would need to be extended to include other important aspects of battery behavior. For battery float life prediction, these aspects would include self-discharge, charging efficiency, transport properties, and degradation processes.

During the third quarter of FY03, SNL focused on the ANN model, while HPRL focused on the ECM (Equivalent-Circuit Model) simulation development. The ECM work included the adoption of a unique feature that separated the ohmic resistance components and faradaic non-linear components into different circuit elements. This model was favored due to its simplicity in describing behavior of an electrochemical system and the success enjoyed in modeling a variety of chemistries, including VRLA.

Due to the lack of suitable data for VRLA, we used data that were available to us via the DOE Advanced Technology Development program for lithium-ion batteries (LiB) to develop the modeling capability and conduct a feasibility study. The SOC-dependent

OCV values of the LiB chemistry used in this work were obtained by discharging a fully charged cell at C/25.

Fourth Quarter Status

Develop Battery Performance Simulation Model using an Equivalent-Circuit (EC)-Based Approach.

Understanding the capacity fade behavior in the 18650 lithium-ion cell performance using the ECM simulation has been continued through this period. In the last report, we showed that, based on the impedance change measured above 60% SOC through thermal aging, we could estimate the cell capacity fade as a function of impedance changes measured at the higher SOC range above 60%. The result did not however accurately predict capacity fade as determined by the reference performance tests (RPTs).

In this reporting period, we conducted more detailed analysis of the capacity behavior of the aforementioned set of test cells and data were collected experimentally to investigate the origin of the discrepancy. Slow rate discharging data indicate that the high lithium content lithiated phases have slower reactivity toward lithium intercalation; the kinetics are sluggish, and thermal aging escalates this process.

To further illustrate the resistance increases in the cell induced by thermal aging, we derived the resistance values as a function of SOC from the discharge curves obtained from the experiments. Figure 3 shows the changes of resistance as the cell goes through the thermal aging, as revealed in each intermittent RPT. The rapid increase in resistance in the lower SOC regime is apparent. We are in the process of dissecting the contributions of the various resistance components in the model to adequately simulate their impacts on the capacity fade.

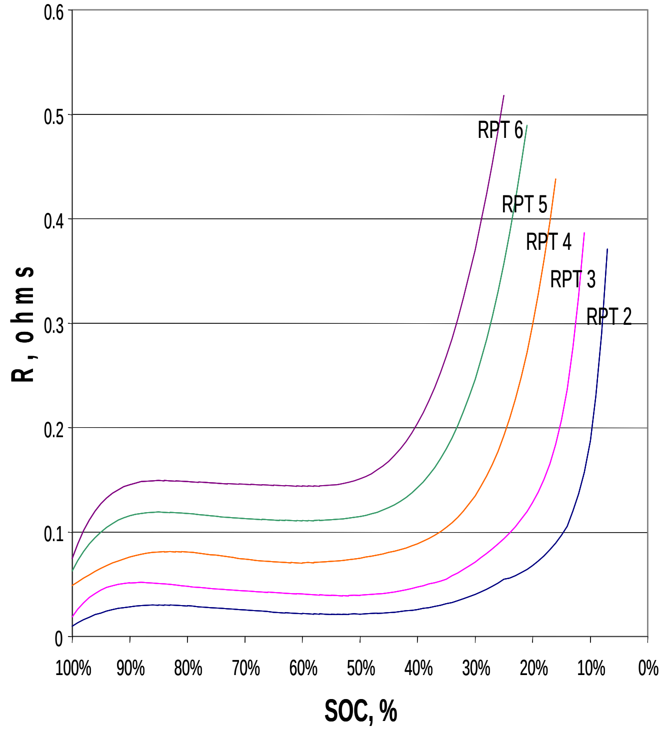


Figure 1. Associated Li-ion cell total resistance changes as a function of SOC derived from the discharge curves.

Further analysis of the resistance changes and the impacts on the discharge behavior will be continued as part of this simulation exercise. The simulation results will be reported in the next report and presented in the upcoming Electrochemical Society Meeting in Orlando, FL.

We have received some initial test data on VRLA storage batteries from Joe Szymborski of GNB. In an initial review of the data, we found the data could be useful for starting some modeling work, but are not sufficient to conduct a thorough analysis of the effect.

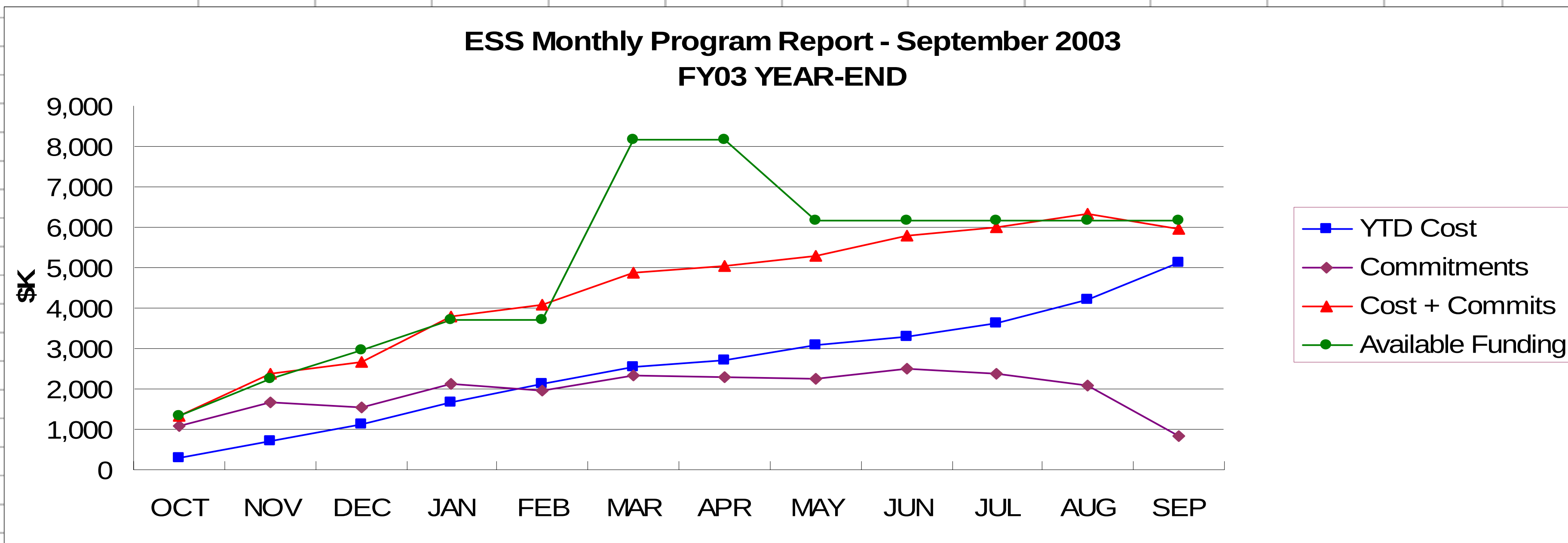
<u>Neural Network Modeling Approach.</u>

The feasibility of using a neural network to model and predict battery charge degradation has been demonstrated. The equivalent circuit model (ECM) provided by Dr. Liaw and Sandia was used to generate surrogate data in the absence of experimental data. A particular type of neural network known as the connectionist normalized local spline (CNLS) was implemented and used in the study. The modeling process involved constructing a neural network as a metamodel to enrich the original data set generated by the ECM. (The data could, in general, be acquired from measurements and/or a phenomenological model.) Data generated from the metamodel were then used in recurrent neural network training.

It has been demonstrated that the recurrent neural network can provide reasonable predictions of the battery discharge capacity over cycles. It was also demonstrated that a recurrent neural network coupled with genetic algorithm adaptation could improve the prediction. Numerical examples have shown that a genetic algorithm can help create low order CNLS neural network models through the optimization of cluster locations and radial basis function widths.

Finally, a principal, components-based uncertainty modeling and quantification technique was used to assess the predictive accuracy of the recurrent neural network. The uncertainty bands estimated by the model successfully captured the discrepancy between the neural network-predicted and metamodel-generated cycle histories. This demonstrates the uncertainty model's ability to assess predictive accuracy.

FOURTH QUARTER FINANCIAL STATUS



	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
YTD Cost	272	701	1,140	1,662	2,126	2,529	2,725	3,068	3,309	3,641	4,224	5,119
Commitments	1,063	1,663	1,526	2,123	1,974	2,349	2,308	2,233	2,495	2,362	2,090	841
Cost + Commits	1,335	2,364	2,666	3,785	4,099	4,878	5,033	5,301	5,804	6,003	6,314	5,960
Available Funding	1,354	2,268	2,954	3,692	3,692	8,169	8,169	6,157	6,157	6,157	6,157	6,157

DOE/ESS Program Milestones (Fourth Quarter FY03)

As of January 28, 2004

Category	Milestone	Performer	Milestone Status (Narrative)	Date Due/ Status
System Integration	Commence Data collection and analyses on the combined 500 kW (Power Quality) and 100 kW / 4 hour (peak shaving) NAS battery system at AEP.	AEP/ Gridwise	The preliminary data analysis and economic analysis reports were presented to American Electric Power (AEP) and SNL during the Sept. 18, 2003 project review meeting at AEP.	7/30/03 Complete
System Integration	Field Test 100kW Li-Ion battery system for 700 hrs at utility sites.	AEP/ SAFT/ SatCon/ Southern Company	Factory test was completed on 5/27/03. The Li-Ion system was shipped on 6/3/03 to American Electric Power (AEP) for installation. As of 9/30/03, more than 700 hours of testing have been completed.	9/1/03 Complete
Subsystem Development	Develop preliminary system requirements for the design, fabrication, delivery, and site testing of a 3 kWh/ 12 kW flywheel system for utilization in hybrid wind/diesel generation systems.	Boeing	In the 4th Qtr FY02, a subscale test system, consisting of a 1 kWh hub design, was built and tested with a 3 kW motor spun up to 12,000 rpm,. Fabrication of the superconducting crystal array for the systems magnetic bearing was completed in the 1st Qtr FY03. In 2nd Qtr FY03, a preliminary System Requirements document was completed. The document defines a flywheel system for hybrid wind/diesel generation systems based on information provided by the Alaska Energy Authority (AEA) on load profiles of several Alaskan villages.	3/31/03 Complete

Category	Milestone	Performer	Milestone Status (Narrative)	Date Due/ Status
Subsystem Development	Initiate high power testing of the ETO prototypes at the Naval Surface Warfare Center (NSWC).	American Competiveness Institute (ACI) / VA Tech / NSWCCD	The final test procedure documentation and the Mission Readiness Panel (MRP) safety review were completed, and testing commenced in January 2003. Testing was halted in mid-April 2003 due to a safety mishap caused by residual voltage (2000V) in the capacitive load bank. The load bank, not the ETO, caused the failure. No further testing was performed while remedial changes where made in the circuit design and test procedure. **Testing resumed the first week of June.** Testing was completed at the end of August, resulting in successful sustained power testing of the ETO for four hours at 2000A/2000V switching frequencies of 500Hz and 1.5kHz. The ETO was also successfully power cycled for one hour at 2000V/400A (1khz) to maximum allowable junction temperature,	7/30/03 Complete
Strategic Analysis	Plan International Energy Storage Conference, EESAT 2003	DOE/SNL/ Energy Storage Association (ESA)	An Organizing Committee representing 5 countries has been established. Brochures were distributed in a general mailing. The EESAT 2003 website is operational and allows direct conference and hotel reservations. Forty abstracts have been received to date. The EESAT 2003 Conference was held in the 1st Qtr of FY04, Oct. 27 – 29, 2003.	9/30/03 Complete

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